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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Rotary Wing Icing Symposium hosted by the US Army Aviation Engineering Flight Activity brought together leading experts in the field of helicopter icing from several countries. In attendance were over 130 military, government and civilian manufacturing personnel representing organizations from the United States, Canada, England, France and Germany. Presentations were given in the fields of flight testing, icing protection systems, flight operations in icing, and icing test

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20. Abstract

facilities. In his keynote address Paul Yaggy, Director of the Unites States Army Air Mobility Research and Development Laboratory, cited the growing emphasis for all weather operational availability. Colonel Dean E. Wright, Commander of the United States Army Aviation Engineering Flight Activity introduced the Army's Helicopter Icing Simulation System and five experimental test pilots of the Activity presented results of icing tests on the AH-1G, AH-1Q, UH-1H and CH-47C helicopters. Military requirements for helicopters capable of operating in icing conditions were discussed in a session chaired by Colonel William E. Crouch, of The Department of the Army. Colonel Horace B. Beasley of the Army Materiel Command was the moderator of discussions concerning new ice protection systems. An international flair was provided during two sessions chaired by Royal Navy Captain J. T. Checketts, British Ministry of Defence and Mr. Alan Wilson, OBE, of the Aeroplane and Armament Experimental Establishment, Boscombe Down. Icing problem areas were found to be similar among the varied types of helicopters from the different countries. Problem areas found to be common were icing of engine inlets, rotors, and windshields. Many varied approaches to solution of these problem areas were exchanged among the attendees which made the symposium a success. This summary report is prepared in three volumes. Volume I includes the symposium opening remarks, papers presented, and discussion in Session I. Sessions II and III papers and discussion are included in Volume II. The closing remarks, presentations, and discussion during Sessions IV and V are contained in Volume III.

PREFACE

The US Army Aviation Engineering Flight Activity acknowledges the outstanding participation of all who attended the Rotary Wing Icing Symposium. The papers presented by the participants were highly informative and of excellent quality. Their contributions played a significant part in the success of the symposium and achieved the aim of the conference to provide an exchange of information concerning operational and test results, testing methods and facilities, and protective measures.

PROLOGUE

Questions to authors and discussions were recorded on magnetic tape. Recording system and procedural inadequacies rendered certain portions inaudible. Mr. Hayden edited the tapes and attempted to paraphrase the comments to convey the sense of the conversation. Should any transcriptions inadequately describe the intended comment or response, please direct your wrath to Mr. Hayden and your written corrected texts to the US Army Aviation Engineering Flight Activity for literal post publication.

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ANTI-ICING/DE-ICING REQUIREMENTS FOR ARMY HELICOPTERS

CPT JOSEPH L. PIKE ANTI-ICING/
DE-ICING REQUIREMENTS FOR ARMY
HELICOPTERS

US ARMY AVIATION CENTER
ATTN: ATST-D-MS
FORT RUCKER, AL 36360

Good afternoon gentlemen, I'm Captain Pike from the office of the Deputy for Developments, US Army Aviation Center, Fort Rucker, Alabama.

Purpose:

A brief history of Army aviation

The Aviation Center/User needs that pertain to anti-icing/ de-icing equipment.

The Army Aviation Center's experience with the current icing program and . . .

Our anticipated course of action with this program in the months ahead.

History

As many of you know, Army aviation has experienced a steady growth since its birth on 6 June 1942, with a somewhat accelerated rate having been experienced over the past 10 years. The aircraft inventory has grown from 10 L-4 observation aircraft, the type which was used in World War II, to the current figure of approximately 10,000 rotary and fixed wing vehicles. Our mission has evolved from one of aerial observation to one of support for all five of the ground combat functions, that is, Command Control and Communications, Intelligence, Mobility, Firepower and Service Support. This growth is attributed, both in terms of number of aircraft and mission, to the valuable services Army aviation rendered during World War II, the Korean War and the Vietnam Conflict. As a result, Army aviation today is a proven member of the Army's fighting team. Wherever the United States Army goes, so goes its organic aviation.

It is important to note that Army aviators have not forced this growth. The case is quite the contrary, Army aviation has flourished by responding to the needs of using ground units and unit commanders. These commanders have initiated and demanded many of the functions and missions that are today considered as established doctrine and procedures. Our future success is

dependent upon our ability to continue to meet these needs.

Background

Of particular interest here today, is the need for helicopters capable of sustained operations in an icing environment. The current fleet of Army helicopters do not possess such a capability. However, if the helicopter is to be considered as an effective combat weapon in areas where these conditions often prevail, such as Europe, the need for this capability is obviously justified. The need is further justified by the fact that those nations constituting the threat in the European Theatre allegedly have an anti-ice/de-ice capability with their rotary wing aircraft.

This is not a new requirement nor a recently discovered problem area. Many of the industries and DOD agencies represented here today have conducted studies on helicopter icing and/or tested a variety of prototype systems. Bell Helicopter, for example, began gathering data in this area over 20 years ago.

User Needs

We at the Army Aviation Center became involved with the helicopter "Icing Problem" in 1968 in response to a deficiency noted by the United States Army in Europe. The crux of the problem, as stated by USAREUR, was that the lack of an anti-ice/de-ice capability presented a significant deterrent to helicopter missions in their area of operations. The problems and consequences associated with this deficiency were later highlighted in a letter between 15th Aviation Group and USAREUR safety officer. The significant points were: (1) Weather conditions in Germany are subject to rapid change, making them difficult to forecast. As a result, aviators are often caught in isolated local weather conditions. (2) Assuming that helicopters are prohibited from flying when ceilings are less than 1500 feet (due to icing conditions) a total of 55 days during October-March can be expected to be non-flying. (3) The topography of West Germany is characterized by severe changes in terrain elevation and when combined with low ceilings and icing conditions difficult flying conditions exist. (4) Presently, the only means that helicopter pilots have to cope with such a combination of problems is to avoid the regions characterized by this adverse combination of weather and terrain.

As the user representative and in an attempt to resolve the deficiency, the Aviation Center researched in excess of 70

documents on this subject. Our findings, quite obviously, were that there were no existing means of satisfactorily correcting the situation. Therefore, we drafted a Qualitative Materiel Development Objective (QMDO), a requirements document, in June 1968 to initiate research and development in this area. The goal was for a system that would provide protection against moderate icing conditions. The QMDO was approved by Department of Army in August 1969 and the development responsibility was subsequently assigned to the United States Army Air Mobility Research and Development Laboratory (USAAMRDL).

Their approach to the problem, in essence, was to follow the recommended course of action outlined by the QMDO Plan. That is to conduct: (1) A detailed study to determine the environmental conditions conducive to moderate icing. (2) Further studies to determine the type of ice detection and protection that would be most advantageous for VTOL aircraft in military missions. To include data on maintainability, reliability, cost effectiveness, aerodynamic penalties, degree of modification to existing aircraft and weight. (3) Installation of prototypes on a test bed with tests being conducted both in ice wind tunnels and using a spraying rig, these tests then were to be followed with tests in natural icing conditions.

Once the program was funded, which wasn't until fiscal year 1972, the developer proceeded to accomplish these tasks. The recommended preliminary studies have been completed, with the follow-on tests and prototyping currently being accomplished through the efforts of our host, the Aviation Systems Test Activity, and the Lockheed Company of California.

Lockheed's system is currently under development and is scheduled to be tested in January and Feburay 1975. The Aviation Center is optimistically looking forward to the January and February 1975 tests. We are hopeful that the system will prove feasible thereby placing the program closer to the objective of getting this equipment to the field units where it is so badly needed.

The fact remains, however, that the needs of the Aviation Center/User for anti-ice/de-ice equipment, are basically the same today as they were when we drafted the QMDO in 1968. That is, we need a system that is capable of resolving the following problems in conditions up to and including moderate icing: (1) Severe vibrations caused by asymmetric shedding of ice from the rotor systems. (2) A gradual deterioration in performance due to ice formation on the airfoil. (3) Damage to the airframe, engine and components due to ice self-shedding. (4) Inability of operating personnel to recognize the extent of ice accretion

in time to effect a precautionary landing. (5) Weight penalties and control problems incurred through a build-up of ice on the fuselage and surfaces of the aircraft.

Conclusions

It is our position that a system of this type is urgently required to enhance the safety and survivability of flight crewmembers and to more closely align the availability of our aircraft with the round-the-clock support ground commanders require.

In this regard, our past efforts in this program have been directed toward actions that we believed would expedite the research and development process. The following are representative of some 20 actions taken by the Aviation Center over the past 5½ years: (1) In June 1970, the Aviation Center forwarded a letter to Headquarters United States Army Combat Development Command (USACDC) recommending that development priority be upgraded from Priority III to Priority I. Also, a concurrent proposal was made that a field test be conducted in Europe to define actual icing phenomena and their effects with a proposed scope of test provided. The priority was upgraded to Priority I. (2) In July and November 1970, industry (Bell Helicopter) submitted two unsolicited proposals to conduct field tests with the UH-1 aircraft equipped with ice protection systems to demonstrate that the helicopter can operate under icing conditions and to establish valid design criteria. The Aviation Center supported these proposals and forwarded them to United States Army Materiel Command (USAMC) as a possible expedient in the R&D effort. Neither proposal was accepted. (3) In June 1973, a draft proposed required operational capability document was submitted to Headquarters TRADOC for review and approval. The document was favorably received, however, the decision was made to change the document to an Operational Capability Objective. This was due primarily to the present efforts in the program and the type funds beign expended. Our future efforts will be characterized by this same type endeavor.

Closing

Army aviation cannot afford to become a part-time member of the Army's fighting team. The development of an effective anti-ice/de-ice system would be a major step toward preventing such an occurrence.

DESIGN AND DEVELOPMENT OF SIKORSKY HELICOPTER PROPULSION ANTI-ICE SYSTEMS

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Stratford, Connecticut

ABSTRACT

This paper describes the design and development of Sikorsky helicopter propulsion Anti-Ice Systems. A brief description of system design requirements, including relevant icing environmental criteria, is included.

The design selection criteria and utilization of the three fundamental types of propulsion anti-ice systems is presented. Specifically included are examples of electro-thermal, engine bleed-air, and inertial type anti-ice systems. Basic design analysis techniques are summarized and specific Sikorsky applications are referenced, including the systems installed in the CH-53, SH-3, and CH-54 helicopters.

Actual development test results in both the NASA Lewis Icing Research Tunnel, Cleveland, Ohio; and the Helicopter Icing Spray Rig of the National Research Council at Ottawa, Canada are discussed.

INTRODUCTION AND BACKGROUND

Sikorsky Aircraft has been providing propulsion anti-ice systems on gas turbine powered helicopters since 1960. Successful designs have been incorporated in the S-58T, S-61, S-65, S-64, and the S67 helicopters. The YUH-60A (UTTAS) design is currently under development. Future helicopter ice protection systems must be consistent with current military philosophy which stresses operation in the European Theater as well as Southeast Asia, upon which concern centered in the nineteen sixties.

Helicopter design requirements are directly related to the liquid water content of the free air, the mean water droplet size, the ambient air temperature, and the local air velocity and surface geometry. The latter two parameters combine to yield the local value of "collection efficiency" which is the measure of the percentage of super cooled droplets which actually impinge on the subject surface.

The selection of specific environmental design criteria for propulsion systems is usually established consistent with those of the engine in the case of Army helicopters. Specifically, the YUH-60A inlet specification is identical with the GE-T700 requirement. Navy specifications have generally referenced the applicable sections of FAR - part 25, appendix C. A typical specification is the CH-53A which requires the inlet to meet the following two criteria.

a. The system shall provide ice protection for the engine air inlet during all flight conditions from hover through 150 knots under the normal design icing meteorological conditions of Figure 1 of FAR Part 25 in the ambient temperature range between plus 32°F and minus 4°F, inclusive.

b. Ice accretion on anti-iced portions of the engine air inlet shall not exceed 1/32 inches thickness in flights lasting three minutes, from hover through 120 knots under the extended icing meteorological conditions of Figure 4 of FAR Part 25 in the ambient temperature range between plus 32°F and plus 5°F at volume median droplet diameter of 30 microns.

These two requirements are shown in Figure (1).

FAR Part 25 also sets the design criteria for commercial applications. When specifications are not clearly established Sikorsky has elected to design the engine air induction anti-ice system capable of meeting the FAR intermittent maximum atmospheric icing conditions from hover to the maximum speed of the helicopter. This requirement is usually satisfied by designing at an ambient temperature of -22°F, in the air with a liquid water content of 1 gm/cu meter, and a mean moisture droplet diameter of 20 microns.

ANTI-ICING SYSTEM DESIGN SELECTION

The selection of the type of propulsion anti-ice system often depends on the availability of the thermal power source or the facility with which an inertial system can be adapted. An engine-bleed air anti-ice system, while requiring between 2 and 3 times the power requirement of an electrical system, is usually far more reliable and less prone to mechanical and electrical failure. Furthermore, a bleed air system can usually better meet "design to cost" as well as maintainability and reliability criteria. However, in the case of relatively complex shapes, significant engineering design and fabrication effort is usually required to control the localized double wall heat

FAR PART 25 MAXIMUM ATMOSPHERIC ICING CONDITIONS

CH 53A ENGINE AIR INLET GUARANTEED PERFORMANCE PER CH 53A MODEL SPECIFICATION

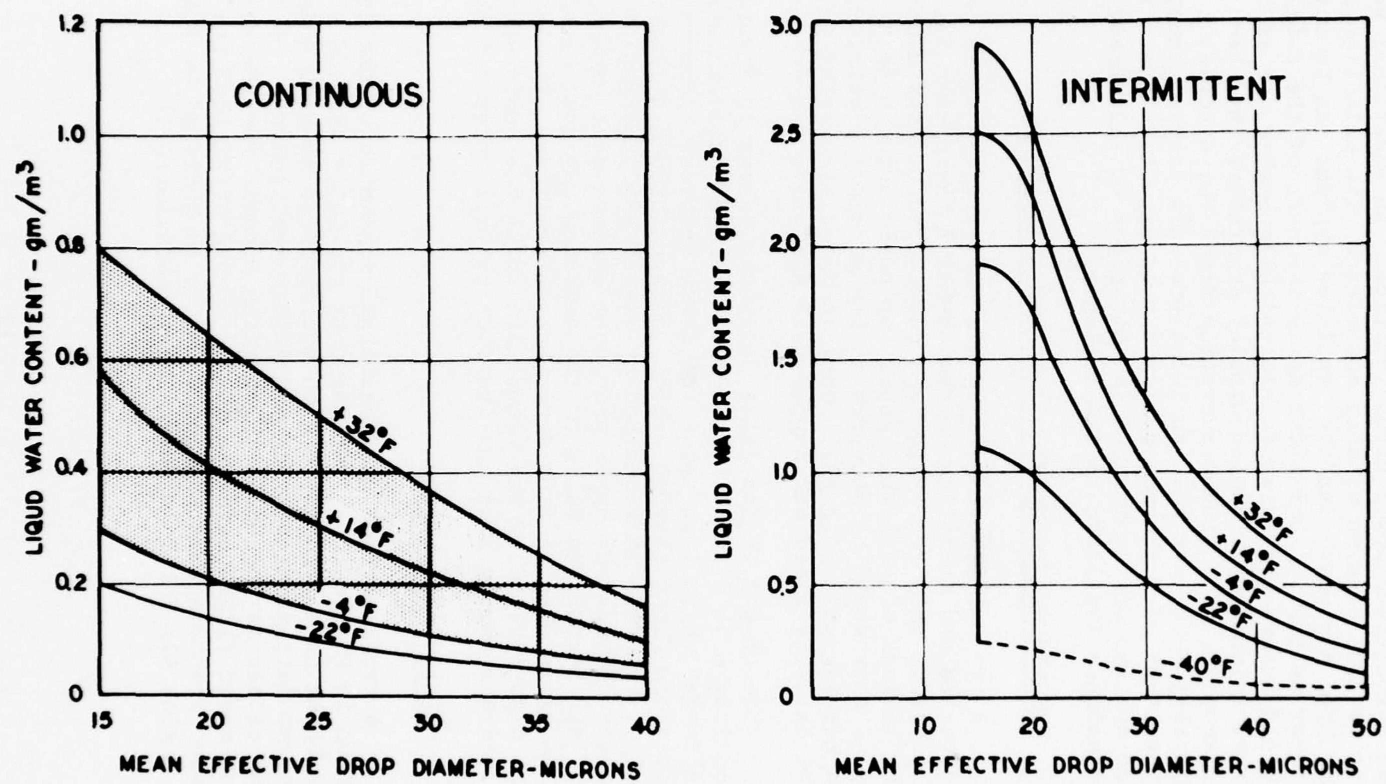


FIGURE 1

exchanger gap height and/or fin spacing, film slots, as well as the associated flow control features. An additional weight penalty (up to 30%) is also usually associated with selection of bleed air type systems. Inertial anti-ice systems can be utilized either as partial solutions as in the case of the S-61 snow/slush shield, where the inlet is electrically heated, or in those cases where actual super cooled droplet separators have been provided to keep an inlet plenum accretion free; for example, the UACL/ Sikorsky S-58T design. An inlet pressure drop at least three times that of a thermal system can be expected here. Three anti-ice systems are summarized in this paper to illustrate the various techniques available to the designer.

ENGINE BLEED AIR ANTI-ICE SYSTEM EXAMPLE

A typical Sikorsky bleed air anti-ice system is that installed and operating on the CH-54A/B (Reference 1). An electrical anti-ice system was considered but was discarded due to lack of available generator power and the major modifications that would be required in the aircraft electrical system. In keeping with this philosophy, a bleed air system incorporating the existing bleed air supply hose and valve was designed.

The CH-54A engine inlet bellmouth, shown in Figure (2), consists of a distribution manifold and a double skin heat exchanger split into upper and lower sections. Compressor exit bleed air flows through a hose, passes through a flow control valve, enters a manifold and by way of 326 impingement holes passes through the upper and lower surface heat exchangers. The hot air scrubs the walls of the tapering gap heat exchanger and then exits through flow distribution orifices. The latter control the distribution of the bleed air, while the resistance in the bleed air supply line and the flow control valve set the quantity.

DESIGN DESCRIPTION

A cross-section and functional schematic of the inlet is shown in Figure (2). The shape of the outer skin of the inlet is based on a lemniscate with modification at both ends to accommodate manufacturing and design requirements. A lemniscate was chosen as the basic inlet shape because for the relatively low speed flight envelope of the CH-54A it yielded the lowest inlet pressure loss and could easily be modified to suit the EAPS - Engine Air Particle Separator - installation.

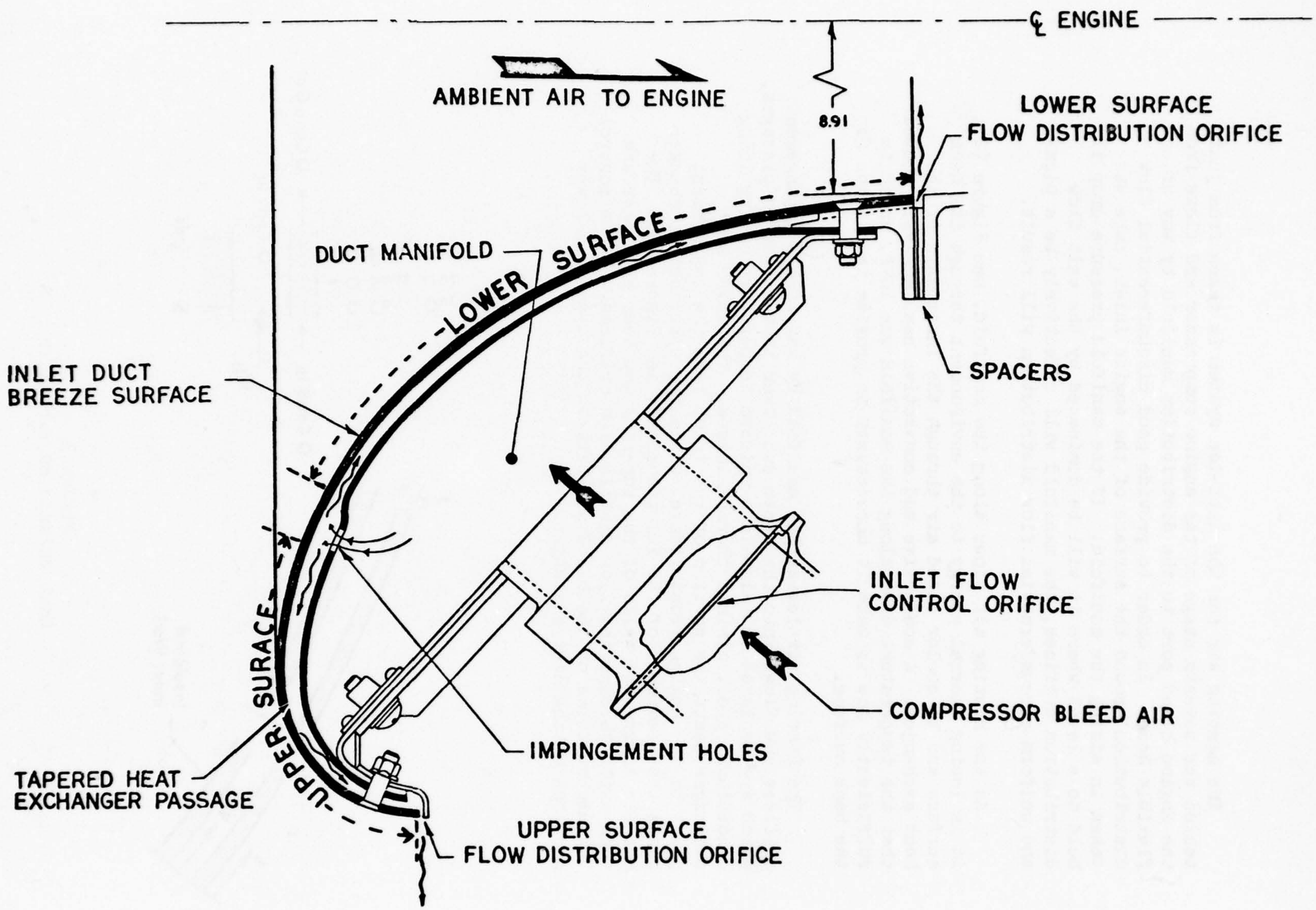


Figure 2
Cross Section of Engine Air
Inlet Duct Anti-Icing System

The heating air for the anti-ice system is taken from just behind the seventh stage of the engine compressor and flows from the engine bleed port to the distribution manifold by way of a flexible hose. In order to provide good circumferential flow distribution around the surface of the engine inlet, care was taken in sizing the manifold. If the manifold pressure drop is held to a level where it will be dominated by the exit flow distribution orifices, the manifold will effectively be a plenum and uniform circumferential flow distribution will result.

As the heating air flows along the manifold, see Figure (2), it is losing thermal energy to the environment through its back surface and to cooler bleed air through the inner skin of the heat exchanger. A conductive and convective heat analysis showed that the temperature drop along the manifold was 10°F, which is sufficiently low to make it unnecessary to provide insulation for the back surface.

The heating air leaves the manifold by way of 326 impingement orifices and flows into the upper and lower heat exchanger passages, which are designed to maintain a uniform temperature during icing conditions; i.e., minimal thermal losses. The lower heat exchanger heats the portion of the inlet from the impingement point to the engine front flange, while the upper heat exchanger heats the remainder of the inlet surface, see Figure (2). The hot air scrubs the walls of the tapering gap heat exchanger and then exits through the flow distribution orifices. These control the distribution of the bleed air between the upper and lower sections of the heat exchanger.

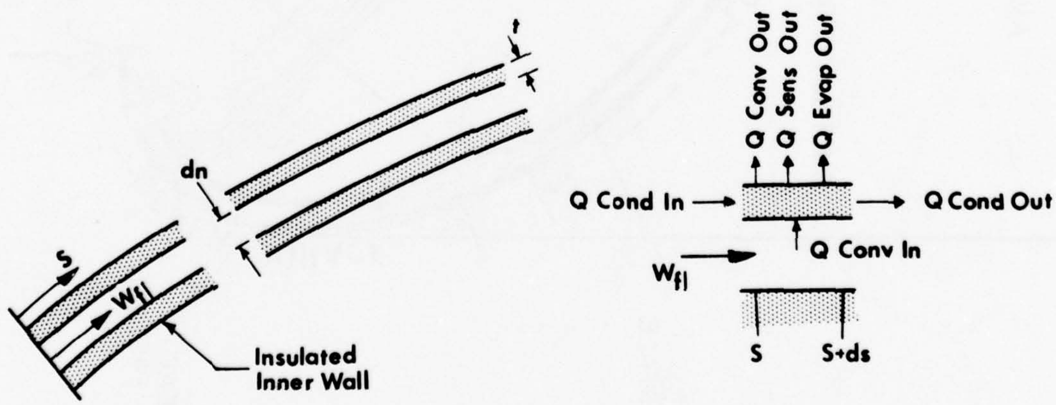


Figure 3
Heat Balance on Exchanger

A heat balance on a section of the heat exchanger is shown schematically in Figure (3). The following energy balance equations can be written, assuming the inner wall is adiabatic;

Q cond. in + Q conv. in = Q cond. out + Q conv. out + Q sens. out + Q evap. out and (1)

heat lost by heating air = Q conv. into outer surface (2)

If Tw is constant, a condition which will yield a minimum thermal energy expenditure, the above equations yield the following expressions for gap height and air flow temperature, vis;

$$dn = 0.0015\, K_a \left(\frac{2Wa}{P\mu}\right)^{0.8} \frac{Pr^{1/3}\,(Ta - Tw)}{ho\ (tw - T\infty) + \frac{2.9\ ho\ Lv}{Pamb}(Psn - Pw)} \qquad (3)$$

$$\frac{dTa}{dS} = \frac{-P}{Wa\ Cpa}\left(\overline{ho}\ (Tw - Too) + \frac{2.9\ ho\ Lv}{Pamb}(Psn - Pw)\right) \qquad (4)$$

Equations (3) and (4) were solved numerically on a Univac 1108 computer using the boundary condition Ta = Ta initial at S = 0, and also the condition that the minimum value of the gap height must be equal to a previously determined value of 0.070 inches, which was consistent with manufacturing and assembly limitations. The ideal gap distribution thus produced was unsuitable for manufacture, although it was the optimum design thermally, because it was slightly non-linear. The ideal gap distribution was therefore linearized and used as input for another computer program to determine the predicted wall temperatures resulting from the actual design gap distribution. This computer program calculates wall temperature and air flow temperature, given a gap distribution and suitable boundary conditions.

The heating air, as it passes through the upper and lower heat exchangers, is subjected to different thermodynamic conditions which require that it be divided unequally between the upper and lower heat exchangers. The procedure was complicated by the need to consider the effect of manufacturing tolerances on the wall temperatures. A maximum error of .020 inches was anticipated between the proposed "design" air gaps and the final assembled inlet. Since the height of the designed heat exchanger passages varied from 0.250 to 0.070 inches, the effect of tolerances on the wall temperature could be appreciable.

The change in gap height from the nominal design values effects the velocity of the heating air, hence, the internal heat transfer coefficient. An increase in the dimensions of the heat exchanger passages resulted in the wall temperature being less that the designed temperature while a decrease had the opposite effect of too high a temperature. The worst tolerance condition; i.e., that which required the most engine bleed air to meet the minimum surface temperature requirement of 40°F, was found to be -0.020 inches at the entrance of the heat exchanger varying to +0.020 inches at the exit. This is because too much thermal energy is expended at the beginning of the heat exchanger where the gap height is small. Thus, the heating air arrives at the end of the exchanger at a reduced temperature. This effect is in addition to the reduced local heat transfer coefficient which will result from an exit gap height which is larger than the design value.

Figure 4
Prototype Inlet Installed In
The Icing Research Tunnel

EXPERIMENTAL RESULTS

The CH-54 engine air inlet was installed in the NASA icing research tunnel, Cleveland, Ohio (see Figure 4) and was tested in ambient temperatures of +40°F, +14°F, -4°F, and -18°F at 110 knots with minimum engine power. A temperature of -18°F was the effective low limit of the tunnel. No traces of ice or frost were observed on the inlet surface. Thermocouple measurements substantiated that the breeze surface temperature did not go below the freezing point during the entire test.

The local value of surface temperature is a function of the aircraft flight speed, gross weight, and environmental conditions. The liquid water content and mean effective droplet diameter were chosen to correspond to the maximum intermittent atmospheric icing conditions given in FAR Part 25, Appendix C, Figure 4. At 110 knots, the tunnel spray system produces a liquid water content versus droplet diameter characteristic which intersects the required maximum intermittent icing condition curve at the following points:

Air Speed Knots	Temperature °F	Liquid Water Content Grams/ Cubic Meter	Droplet Diam Microns
110	-18	1.27	19.3
110	-13	1.32	20.5
110	- 4	1.44	22.0
110	14	1.54	24.0
110	32	1.64	26.0

Table I Tunnel Meteorological Conditions

Figure (5) indicates that the average measured values of temperature along the inlet surface compare well with the estimated band predicted using the analytical procedure previously described. The wide variation in the predicted band is due to circumferential thermal losses as well as manufacturing and assembly gap tolerances. The waves in the predicted results are due to local effects of the bleed impingement and the linearization of the ideal gap distribution.

It is clear that the variable gap double wall design approach, while not as thermally efficient as a finned heat exchanger, can clearly yield results that "meet the requirement." Additionally, the reduced complexity associated with this technique improves

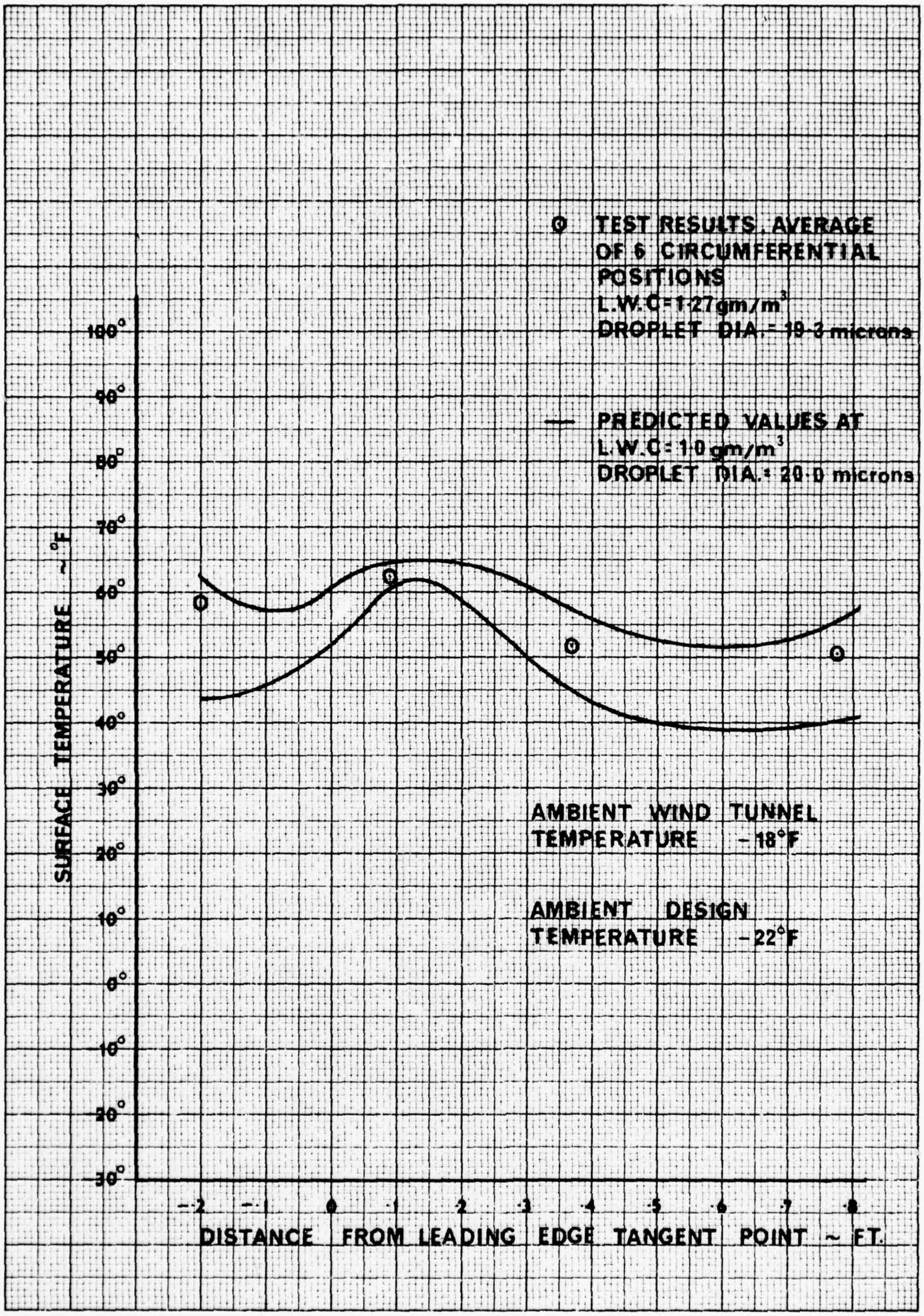


Figure 5
Comparison of Predicted Surface Temperatures
And Test Results at 110 Knots
(CH-54 Inlet)

reliability and maintainability and yields a component which can meet current "design to cost" criteria.

INERTIAL ANTI-ICE SYSTEM EXAMPLE

An example of the analytical procedures developed at Sikorsky to design an effective inertial- anti-ice system is the aerodynamic fairing within the H-3 helicopter snow/slush shield (see Figure 6). The intent of the fairing was to produce internal flow paths adjacent to the inner surfaces of the shield such that any super cooled droplet trajectories which enter the shield inlet do not impinge and form ice or consequential frost.

The analysis consisted of two basic stages:

1. The definition of the potential flow pattern for the air passing through the shield opening and entering the engine bellmouth. A two dimensional approximation using an electrical analog field plotter was actually used in the case of the H-3 to describe the flow pattern. This procedure would be replaced by a digital computational technique to define the potential flow pattern if the fairing were to be developed today.

2. Calculation of the trajectories of the super-cooled moisture droplets: These trajectories are predicted by mathematically equating the aerodynamic and inertial forces acting on the moisture droplets. At any given instant in time, the droplet has an aerodynamic force acting on it which depends on its position and velocity at that instant. This force causes the droplet to accelerate and change its velocity and position. Equating the aerodynamic drag force acting on a droplet to its acceleration yields

$$\overline{D} = m \frac{d\overline{v}}{dt} \qquad (5)$$

where the drag force

$$D = \tfrac{1}{2} \rho_o V_{rel}^2 C_r A \qquad (6)$$

Reference (3) gives the coefficient of resistance of the droplet as

$$\sqrt{C_r} = 0.63 + 4.8/\sqrt{Re} \qquad (7)$$

Substituting equations (6) and (7) into (5) and subsequent algebraic manipulation yields the expressions for acceleration of the droplet in the x and y directions as:

$$\frac{dVx}{dt} = \frac{\pi d\mu}{8m} (0.397\sqrt{Re} + 6.04 \sqrt{Re} + 23.0) (Ux-Vx) \qquad (8)$$

and

$$\frac{dVy}{dt} = \frac{\pi d\mu}{8m} (0.397\sqrt{Re} + 6.04 \sqrt{Re} + 23.0) (Uy-Vy) \qquad (9)$$

Equations (8) and (9) are converted to finite difference form, given suitable entrance boundary conditions, integrated to yield Δx and Δy positional changes over the time increment Δt. The procedure is accomplished using a program developed for the Univac 1108 computer.

Figure 7 illustrates the droplet trajectory path of a 30 micron moisture droplet as it enters the engine with an aerodynamic fairing installed. The shape of the fairing is the result of an iteration procedure. If the resulting trajectories resulting from a given aerodynamic fairing indicate that the moisture droplets tend to intersect the surface, the contour is modified. This procedure continues until an acceptable design is obtained. Of particular importance is the shadow ramp indicated in Figure (7). The ramp is found to be effective in directing droplets outwardly so that they can be ingested by the engine before striking the surface of the aerodynamic fairing.

Due to the repetitive nature of the desired analytical solution, the Univac 1108 computer was used to advantage. The droplet momentum equations derived above were programed. A suitable time increment $\Delta t = 0.167 \times 10^{-3}$ seconds was chosen by a trial and error procedure. In operation, the computer predicts the velocity and position of the droplet at the end of each time increment. The computational procedure requires the droplets to be given an initial position at various points surrounding the intake and an initial velocity equal to the surrounding air (zero relative velocity). The program subsequently predicts the movement of the droplet as it progresses towards the engine. As the droplet moves, it encounters the appropriate change in velocity determined by the potential flow analysis. The relative velocity of the surrounding air acts on the droplet and determines its resulting trajectory.

The procedure described above can also be used to predict the accretion rate and extent of spanwise and chordwise coverage resulting from exposure of a main or tail rotor to a super cooled spray or cloud.

Figure 6
SH-3 With Ice Deflector Installed
(Side View)

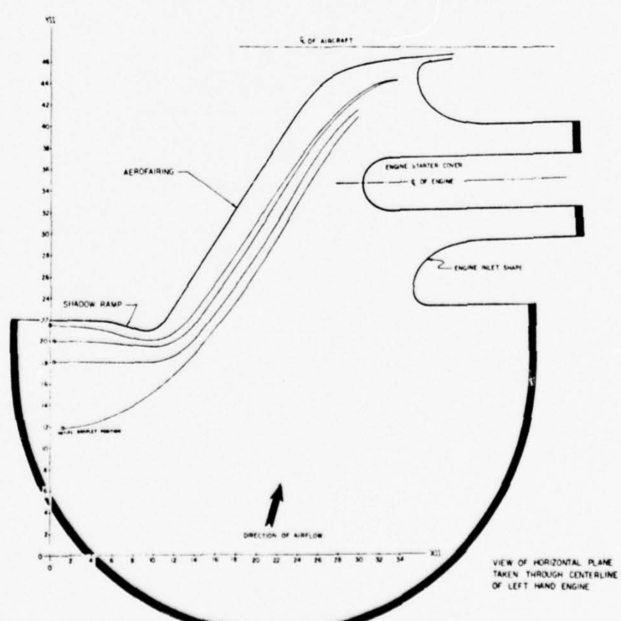


Figure 7
Predicted Droplet Trajectory Paths

EXPERIMENTAL RESULTS

Experimental testing of the H-3 helicopter snow/slush shield with and without the aerodynamic fairing was performed at the Helicopter Icing Rig of the National Research Council of Canada located in Ottawa, Canada. This facility simulates natural icing conditions by use of an artifical steam and water spray cloud. The spray system consists of a welded steel frame with a spray nozzle array measuring 15 ft. high by 75 ft. wide. Steam and water are fed into the atomizing nozzles to produce the icing cloud at temperatures below freezing. Figure (8) shows an H-3 helicopter operating in the icing rig.

A comparison of the results with and without the aerodynamic fairing installed under identical icing conditions (4°F, 0.4 gm/m^3 liquid water content, 12 miles per hour wind speed, and 10 minutes in the spray rig) is shown in Figures (9) and (10). These figures clearly indicate that installation of the aerodynamic fairing produced a marked reduction in the amount of frost formed on the inner surface of the H-3 snow/slush shield.

Future applications of the inertial anti-icing analytical design technique, described above, should greatly enhance the ability of the designer to predict droplet trajectories over aerodynamic surfaces accurately. Ice accretion on many critical areas can thus be prevented or minimized through appropriate use of aerodynamic and inertial forces. This should result in a marked reduction in the use of relatively expensive thermal energy for anti-icing purposes.

Figure 8
SH-3 Helicopter in Spray Rig

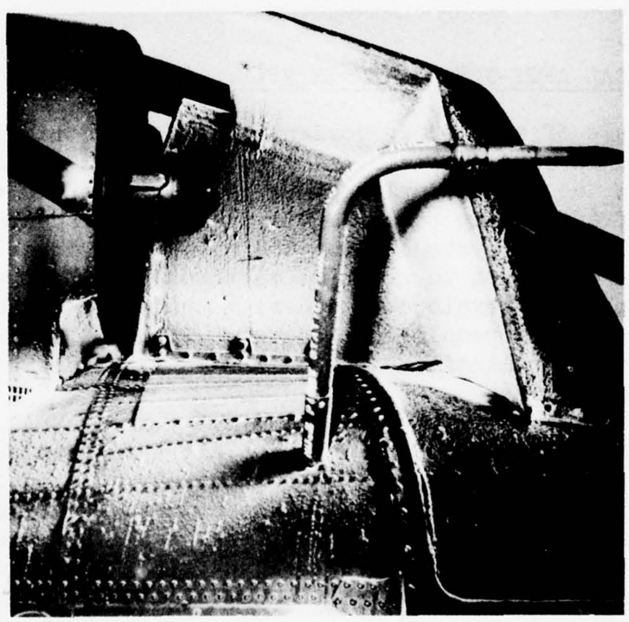


Figure 9
Frost Build-up on H-3 Shield
Without Aerofairing Installed

Figure 10
Frost Build-up on H-3 Shield
With Aerofairing Installed

ELECTRICAL ANTI-ICE SYSTEM EXAMPLE

An example of a Sikorsky designed thermo-electrical anti-ice system is the CH-53 engine air inlet (Reference 4, see Figure 11). In this case, the large complex shape of the inlet and the large variations of anti-icing power density required discouraged the use of the bleed air systems. Additionally, techniques to control the system in order not to overheat sections and thus waste bleed air were not completely developed. A design trade off indicated that the weight and power penalties associated with a bleed air system did not outweigh reliability/maintainability and design to cost considerations.

The inlet was designed to maintain all anti-iced surfaces above freezing during operation in required icing conditions. All moisture impinging on these surfaces is either evaporated or maintained in a liquid state until it runs back into the GE-T64 engine compressor where it is evaporated. It was recognized that the fiberglass matrix into which the heater wires are embedded is a poor heat conductor and that surface temperature gradients

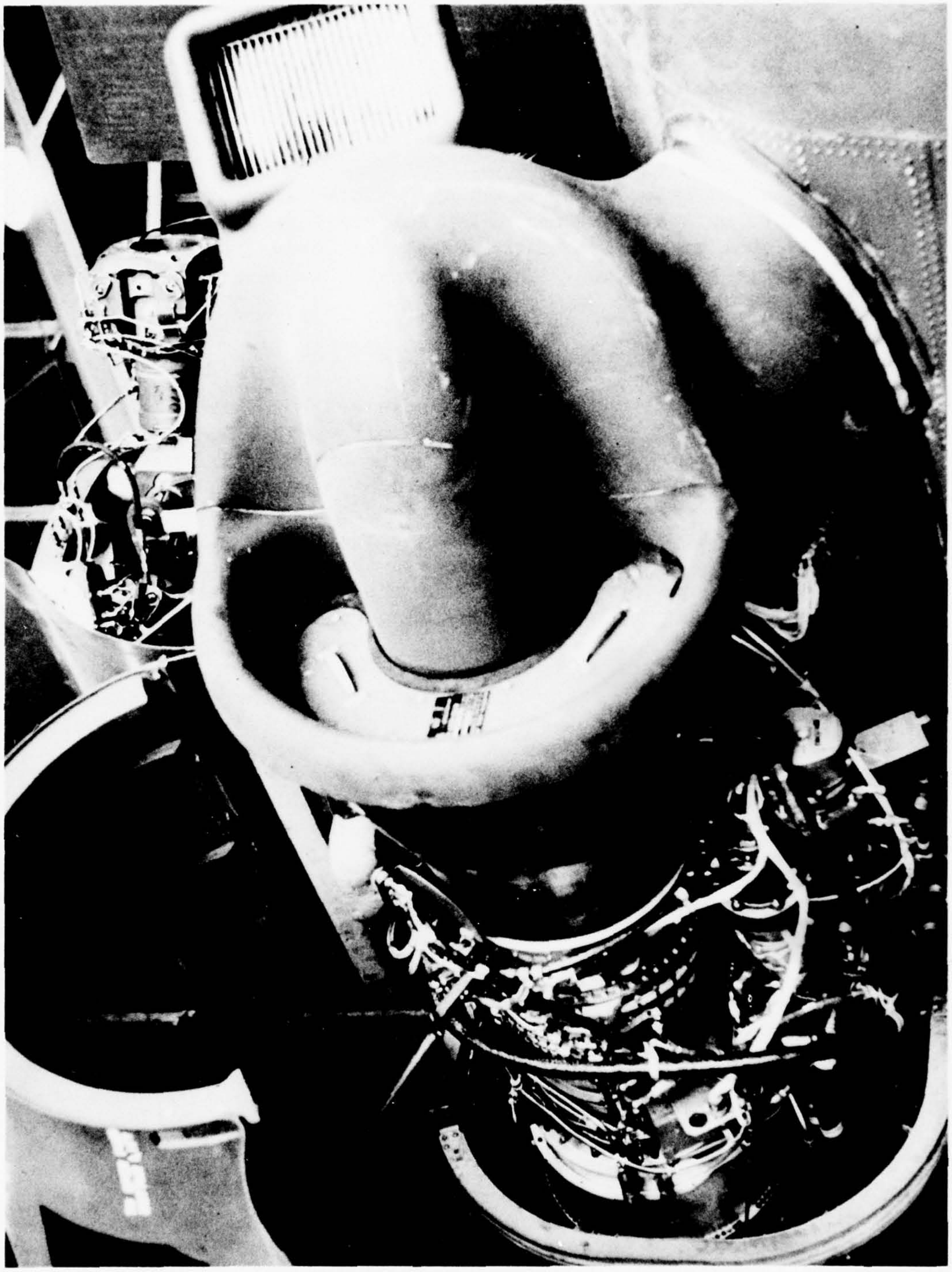


Figure 11: CH-53 Engine Air Inlet

would exist between points directly over wires and points between wires. In order to prevent local surface temperature excursions from dropping below freezing and thereby providing ice nucleation points, the inlet was designed to maintain an average surface temperature of plus 40°F.

As in the case of the bleed air system, the total heat required to maintain the air inlet surface temperature at plus 40°F is equal to the sum of the local convective, evaporative, and sensible heat losses. Approximately 22KW were found to be required per inlet.

ANTI-ICING DUCT CONSTRUCTION AND CONTROL

The inlet duct and associated nose gearbox fairing are fiberglass reinforced molded plastic units with embedded heating wires, as shown in Figure (12). Copper screen is laminated into areas of the duct which are subject to high rates of moisture impingement to help reduce surface temperature gradients. Also, certain local areas contain embedded temperature sensor wires. These sensor wires are used to protect the inlet from over heating. They also warn the crew if anti-icing protection is lost or inadequate for the prevailing conditions.

Power density is varied by varying either the wire spacing or wire resistivity. Prior to lamination into the duct, the heater wires are laid out over a layer of nylon scrim. This scrim holds the wires in place during the molding process.

A study was undertaken to determine the effects of wire spacing variations and to determine what design/formation technique could be practically used to reduce surface temperature gradients where relatively large wire spacings and power gradients existed. The results of this program can potentially be applied to all thermo-electric anti-ice designs.

Figure (13) is a photograph of a test panel used to evaluate the relative merits (elimination of hot and cold spots) of coating the embedded wire heater surface with Dupont 4929 silver conductive coating or embedding a copper screen.

Temperature measurements were made with an infrared camera. This camera scans the target with an infrared detector. The detector output is amplified and used to modulate a glow tube which scans a sheet of film in synchronization with the detector scan of the target. The resulting picture is a thermal map, or thermograph, of the target surface. For each shade of gray in

TYPICAL CROSS-SECTION

CH-53A ENGINE AIR INLET DUCT AND NOSE GEARBOX FAIRING

1. .005 BLACK POLYURETHANE EROSION COAT (CONDUCTIVE FOR ANTI-STATIC)
2. .005 WHITE POLYURETHANE NON CONDUCTIVE
3. .005 FIBERGLASS
4. .006 COPPER SCREEN (LIP ONLY)
5. .005 FIBERGLASS (LIP ONLY)
6. .020 HEATER WIRES
7. .005 NYLON SCRIM
8. SENSOR WIRES (LIP ONLY)
9. .022 FIBERGLASS (.033 OUTSIDE OF LIP)

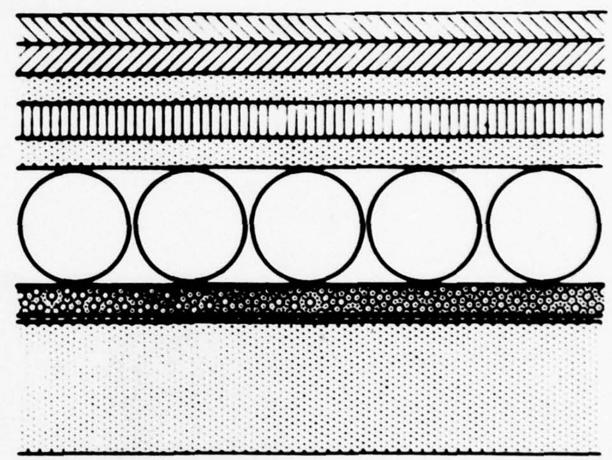
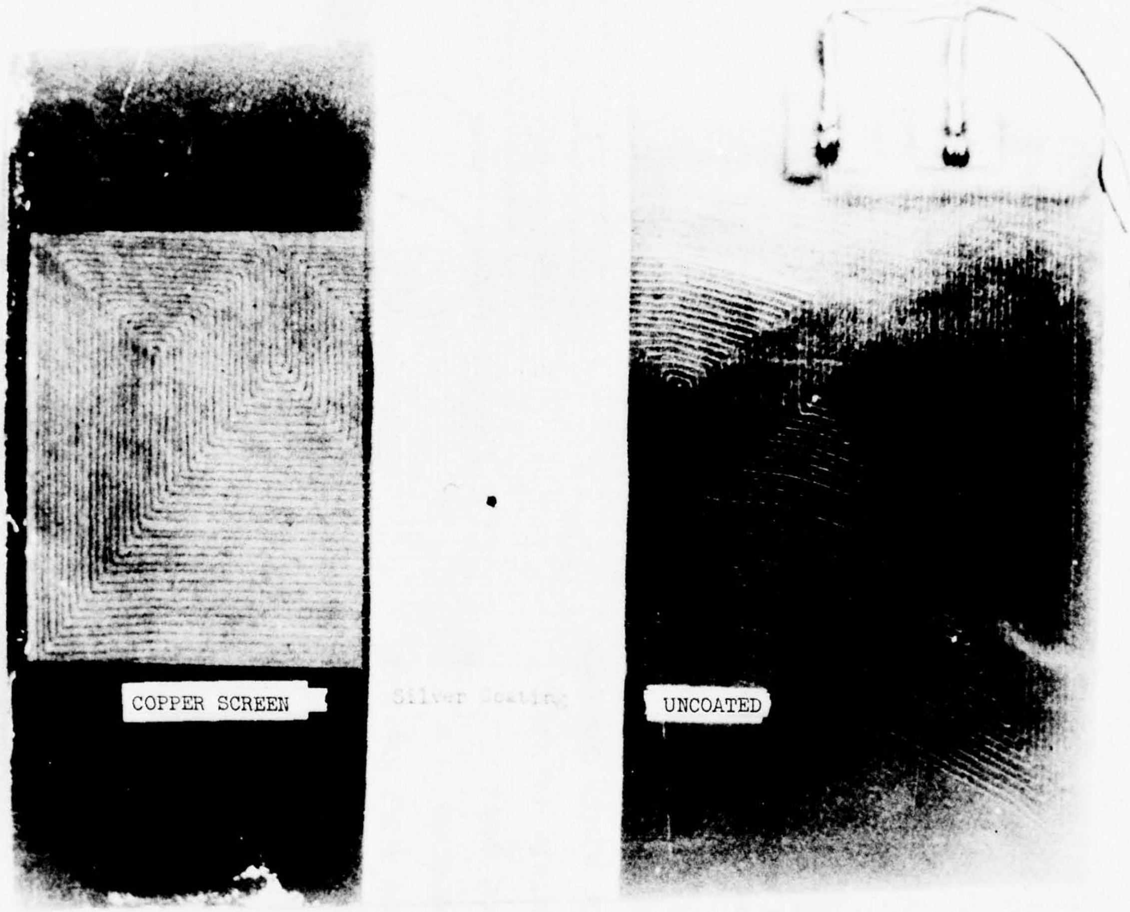


FIGURE 12



BACK SURFACE OF TEST PANEL #1

FIGURE 13

the thermograph, a temperature is calculated to allow an analysis of the target surface.

The resulting panel thermograph shown in Figure (14) indicates that for the subject test panel (heated at 4.7 watts/in^2 and divided into adjacent high and low power circuits, 72.7% and 27.3%, respectively), the embedded copper produced a more uniform temperature distribution than the silver coating. Detailed measurements yield the following maximum temperature gradients: (1) uncoated -32°C; (2) Dupont #4929 silver coating -28°C; (3) 100 count x .002 in etched copper screen - 7°C. This evening temperature trend was later confirmed in subsequent icing tunnel tests in the NASA-Cleveland icing research tunnel. The embedded copper wire approach should be used in thermoelectric designs which require wire spacing of less than 16 wires per inch.

The CH-53 inlet itself was tested in the icing research tunnel. The inlet duct and the associated nose gearbox fairing heating elements were subdivided into 14 and 8 zones, respectively. Each zone contained two parallel circuits, a high and low power circuit similar to the thermograph test panels. Power to each circuit was independent and variable. The minimum power required to prevent ice accretion in each zone could be ascertained.

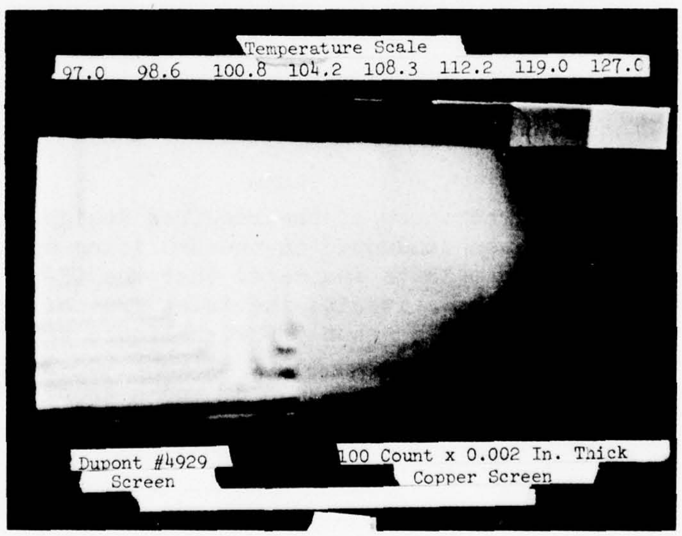


Figure 14
Thermograph of Test Panel #1;
4.7 Watts/In^2 Power Split 72.7%-27.3%

The results of this test indicated that, although the finalized power requirements were within 5% of the original design analysis, additional design modifications were required to produce a satisfactory design. These modifications are all tied to one central theme. Specifically, the hot and cold spots observed during the test had to be eliminated (see Figure 15). The important design modifications/conclusions are given below and should be useful for future thermo-electrical designs:

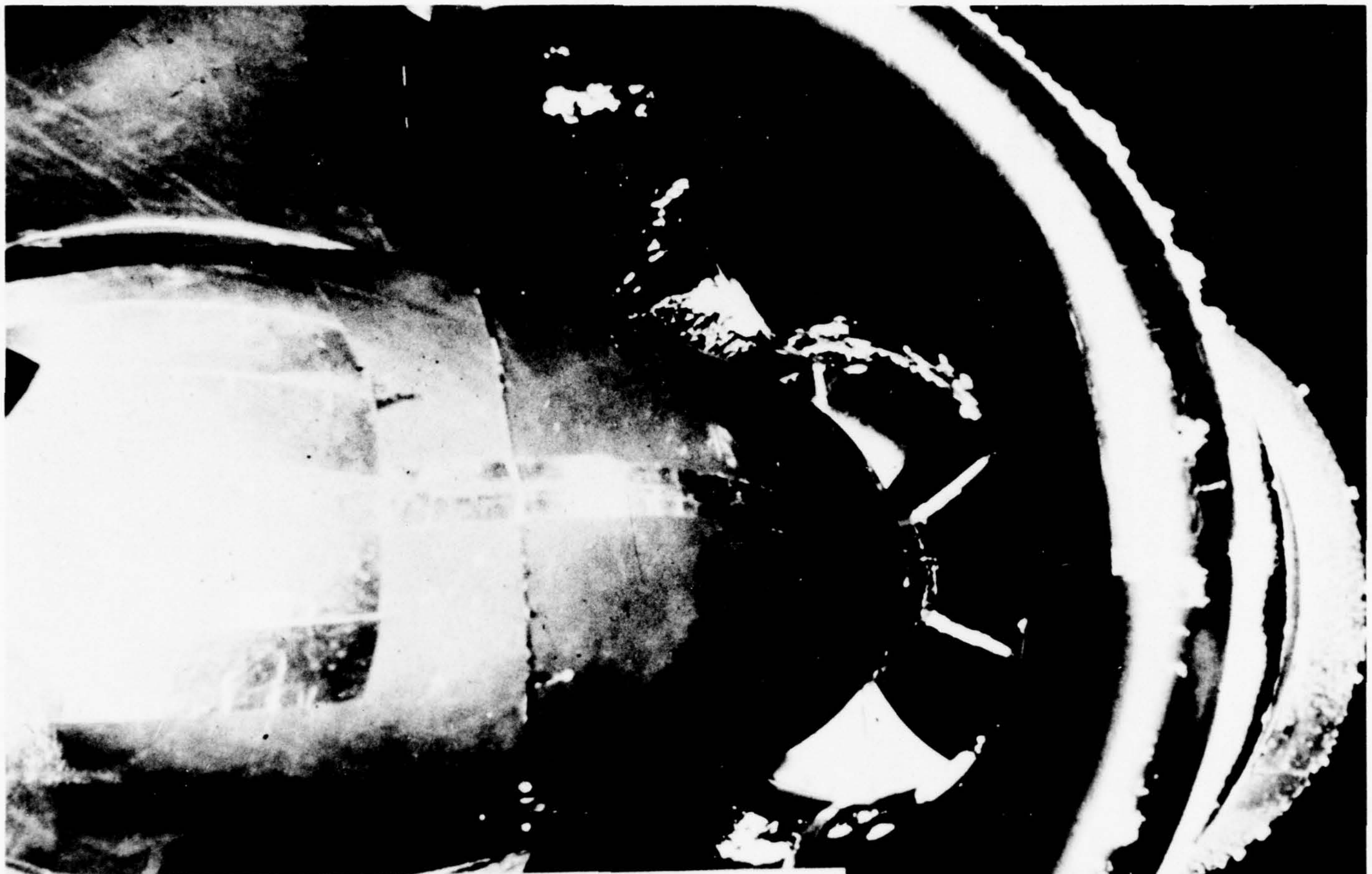
(1) A Y- Δ switching circuit should be used to reduce power by 25% in event of a generator failure.

(2) Heater wire elements should be located normal to the airflow direction (prevents rivulets of warm water from flowing between the wires), turn less than 120° except for required 180° turns, and be spaced at a minimum of 16 and preferably 18 wires per inch.

(3) Copper screen should be embedded where wire spacing is less than 16 wires per inch. This was done in the case of the CH-53A inlet leading edge because of the high watt density demand in this area resulting from a localized lower electrical resistance (large wire spacing).

The CH-53 inlet test was a successful development test in that it established important guide lines for subsequent thermo-electric designs.

Following incorporation of the required design modifications, additional testing was conducted in the NRC icing spray rig, Ottawa, Canada. These tests indicated that the CH-53 engine air inlet anti-icing system maintains the inlet free of ice at all ambient temperatures above minus 5°F with liquid water content ranging from .5 grams per cubic meter at 24°F to .3 grams per cubic meter from plus 1°F to minus 5°F, and a droplet size of 30 microns.



COLD SPOTS CAUSED BY LOW POWER CIRCUIT, WIDE WIRE SPACING, TURN-AROUND AND DIRECTION OF WIRE LAYOUT, RUN NO. 35

True Airspeed 172 mph
Airflow 29.5 #/sec
Tunnel Total Temperature $0^{\circ}F$
Liquid Water Content 0.97 g/cu.m
Droplet Diameter 18.6 microns
Time in Spray 14 minutes

FIGURE 16

Figure 15

SUMMARY AND CONCLUSIONS

The selection of which of the three above described anti-ice systems should be chosen depends on the specific application. Indeed, some designs (see for example the CH-54 EAPS anti-ice system, Reference 5) have utilized all three methods simultaneously. The designer must keep in mind that current helicopter design philosophy is based on "meeting the requirements." This means that he must weigh the relative merits of weight, performance, reliability, maintainability, ILS, and unit cost in reaching a decision. No panacea can be offered and the choices and relative influence coefficients associated with the above parameters are not found in any text book or specification. However, it is clear that the selection process is never limited to the anti-ice system designer alone. Consequently, it is incumbent on him to establish the specific trade off information during the preliminary design period, and not as an after thought.

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<u>NOMENCLATURE</u>

SYMBOLS	UNITS	DESCRIPTION
A	Ft^2	Projected frontal area of droplet
Cpa	BTU/lb ^oF	Specific heat of heating air
C_r		Coefficient of resistance
D	Lb	Drag force
d	Ft	Droplet diameter
dn	Ft	Heat exchanger gap height
ho	BTU/hr Ft^2 ^oF	External heat transfer coefficient
$\overline{ho}$	BUT/hr Ft^2 ^oF	External heat transfer coefficient + sensible heat flux/sq ft
K_w	BTU/hr Ft ^oF	Thermal conductivity of wall
Ka	BTU/hr Ft ^oF	Thermal conductivity of heating air
Lv	BTU/lb	Latent heat of vaporization
m	Lb	Droplet mass
P	Ft	Perimeter
Pamb	PSIA	Ambient pressure
Pr		Prandtl number
Psn	PSIA	Saturation pressure of air at wall temperature
Pw	PSIA	Partial pressure of water in air
Q	BUT/hr	Heat lost or gained over a surface

SYMBOLS	UNITS	DESCRIPTION
Q cond	BTU/hr	Heat lost or gained over a surface due to conduction
Q conv	BTU/hr	Heat lost or gained over a surface due to convection
Q evap	BUT/hr	Heat lost over a surface due to evaporation
Q sens	BTU/hr	Sensible heat lost over a surface
Re	---	Reynolds Number
S	Ft	Surface Distance
Ta	^{o}F	Temperature of heating air
Tw	^{o}F	Wall temperature
T_{oo}	^{o}F	Ambient temperature
u_x	Ft/Sec	x component of air velocity
u_y	Ft/Sec	y component of air velocity
$\overline{v}$	Ft/Sec	Droplet velocity
$\overline{V}rel$	Ft/Sec	Relative velocity
v_x	Ft/Sec	x component of droplet velocity
v_y	Ft/Sec	y component of droplet velocity
Wa	Lbs/hr	Heating air flow
t	Sec	Time
Δx	Ft	Change of droplet position in the x direction during each time increment
Δy	Ft	Change of droplet position in the y direction during each time increment.

SYMBOLS	UNITS	DESCRIPTION
μ	Lb/Ft Sec	Absolute air viscosity
ρ_o	Lb/Ft^3	Air density

THE DESIGN AND DEVELOPMENT OF NEW ICE-SHEDDING COATINGS

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INTRODUCTION

Service requirements for the operation of helicopters in icing conditions have recently placed greater emphasis on the problem of deicing helicopter rotor blades, engine intakes and exterior equipment to enable them to operate in lower temperature environments than at present. A means of improving blade deicing in particular was investigated with the aim of depressing the critical shedding temperature so that some helicopters can operate continuously under icing conditions at much lower temperatures.

Pastes and fluids have been used for many years to remove ice, but have only a temporary effect and are therefore not suitable for continuous deicing on helicopter rotor blades. Heating the leading edges of blades on which ice forms can produce problems due to run-back of water over unheated parts and subsequent re-freezing. Electrical heating would impose a significant weight penalty and the redesign of existing and projected blades to incorporate this facility could be costly both in terms of money and loss of payload. The opinion has previously been given[1] that the use of momentum separation to prevent ice build-up can be safer and as effective as heating without using any appreciable extra power. An inexpensive, lightweight and durable ice-shedding coating for rotor blades would meet many of the requirements for an optimum solution and it was decided to try to develop such coatings, initially for use down to -20°C.

A coating having a flexible substrate which enables ice to peel from the surface has shown promise on Wessex 5 rotor blades and has been recommended for further ice-shedding trials. Versions of this coating are being considered for application to other structures also, particularly installations on ships.

FACTORS GOVERNING ICE SHEDDING

Consider a drop of water at rest on a solid non-deformable surface and making a contact angle with the surface between 0° and 180°. Attractive van der Waals' dispersion forces will operate between the water molecules and the surface and, if the latter is polar, additional orientation and, possibly, induction forces

and hydrogen bonding may occur. These forces will persist after the water drop freezes, although the stresses induced during solidification and expansion of the ice may weaken the bond, so that ice will adhere to some extent even if the surface is non-polar and presents a high contact angle to water. The greater the contact angle, the lower the proportion of water molecules in the drop in contact with the surface and also, after freezing, the lower the area of adhesion per unit volume of ice. A low energy surface presents a greater contact angle to water than does a high energy surface and should therefore adhere less well to a given volume of ice[2,3]. A low energy surface also tends to assist the formation of air bubbles at the ice-surface interface, which weakens the adhesion[4]. In practice, there are limits below which surface energies of solids cannot be lowered further; the lowest critical surface tension of a polymer in common use is about 18.5 mN/m for polytetrafluoroethylene[5] although lower values have been reported for some experimental polymers. As expected, ice adheres to some extent to polytetrafluoroethylene when the polymer is in the form of a block thick enough for the surface to be inflexible, so a low surface energy alone is not necessarily the only parameter to be considered when devising a surface having low adhesion to ice.

To remove ice from the surface of a non-deformable material, a crack must be initiated and propagated between the ice and the surface. The ice/material may be considered from the mechanical viewpoint as a stiff single continuum; an analogous situation exists in an aluminium lap joint in shear using a brittle adhesive, where the stress distribution is similar to that in solid aluminium having an identical geometry to the lap specimen[6]. If a tensile load normal to the plane of the interface is applied to the ice/material composite, failure will occur by crack opening and, if the adhesive forces are greater than the cohesive strength of either ice or the material, cohesive failure in the weaker phase rather than separation at the interface will result. If, however, ice is bonded to a deformable surface, then the application of tensile stress normal to the plane of the interface would give rise to some shear stress at the interface, having a maximum value at the edges of the sample, and would tend to give rise to failure by peeling. Since the applied stress is concentrated on only a very limited area of the interface at any one time during peeling, the load required to part an adhesive from an adherend by this mechanism is usually much less than that required to part the same materials when under tension. The tensile and resultant shear stresses necessary to remove ice from a suitably flexible surface should there-

fore be less than those required to remove ice from a non-deformable material having otherwise identical surface properties.

The Griffith crack theory, $\sigma \cong \sqrt{\frac{2E\gamma}{\ell}}$

where σ = failing stress
E = elastic modulus
γ = surface energy
ℓ = crack length

predicts lower values of σ than are found experimentally. The theory has been modified[7] to include a term, ψ, representing irreversible work done on opening a crack, which is dissipated as heat, or in creation of dislocations or on plastic deformation. Thus the modified Griffith equation becomes

$$\sigma \cong \sqrt{\frac{2E(\gamma + \psi)}{\ell}} .$$

The factor ψ, which is numerically much greater than γ, is linked with fracture toughness and it is believed that this property is increased by plastic deformation at the crack tip[8]. The removal of ice from a surface should therefore also be facilitated by the absence of plastic deformation under stress in the surface to which the ice is adhered. A surface which is sufficiently flexible to allow peeling to commence yet is stiff enough to propagate a crack once it has formed appears to be the compromise required to promote ice-shedding under load.

A practical means of making the required deformable surface is to bond to the existing structure a composite comprising a sponge rubber substrate carrying an impermeable and flexible film. The flexibility of this composite will depend on its composition which can be varied according to the requirements of the particular application. Only a relatively thin composite, certainly not more than about 2 mm thick, would be permitted for application to existing helicopter rotor blades since, at present, the effect of leading edge coatings on the aerodynamic properties of blades is difficult to predict. With the foregoing observations in mind, metal and non-metal surface films were chosen for examination for ice adhesion in conjunction with both flexible and inflexible substrates.

PREPARATION OF SAMPLES

Samples for laboratory measurements

Non-metallic surface materials examined were low density

polyethylene (PE) film, polytetrafluoroethylene (PTFE) film, polyurethane (PUR) sheet, polyvinyl chloride (PVC) tape and nylon 66 film. Thicknesses of these films and of the various substrates used with them are given in Tables 1-5. Metal foils used for surfaces included spring steel, phosphor-bronze, copper-beryllium and stainless steel alloys; details are given in Table 6.

The PE films were pre-treated on one side only. The surface was first roughened with emery paper, then treated with chlorosulphonic acid for 30 minutes at room temperature[9]. After washing well with water and drying, the new surface adhered to the substrate satisfactorily using a rubber-based adhesive which did not cure by solvent release, thereby minimising bubble formation in the adhesive layer.

Each PTFE film was pre-treated on one side with a solution of sodium (23g) and naphthalene (128g) in tetrahydrofuran (1 litre) for about 1 minute, washed with water and dried prior to application of the adhesive.

Two types of PUR sheet were investigated; a clear unfilled grade and a filled rain erosion resistant PUR to Specification WGPS 240. These sheets were roughened with emery paper on one side, cleaned with ethyl acetate using a lint-free cloth and dried before application of the adhesive. The PVC tape was self-adhesive.

Metal foils were degreased and bonded to the substrates using a rubber-based adhesive.

The flexible substrates comprised a commercially-obtained closed-cell foamed natural rubber of medium hardness and an open-cell natural rubber sponge, which was softer than the closed-cell foams.

The surfaces and substrates measured about 100 mm x 80 mm and the composites were bonded to somewhat larger (about 150 mm x 100 mm) rigid aluminium alloy backing plates 1.5 mm thick using a rubber cement. The films were also bonded directly to identical backing plates for comparative purposes.

Test panels were also prepared, measuring about 150 mm x 150 mm, in which the outer skins of PE or PTFE films were attached to open-cell foamed natural rubber substrate, bonding only the edges of the specimen. Specimens were also made comprising spring steel, copper-beryllium and phosphor-bronze strips,

0.25 mm thick, 15 mm wide and about 500 mm long suspended by their ends only in an open frame so that they could flex with respect to the frame.

Samples examined in icing chamber

Flat sheets about 600 mm^2 comprising the composite coatings on rigid metal backing plates were prepared and subjected to rime and glaze icing conditions in an 'arctic chamber'. The samples included PE film on closed-cell foamed natural rubber (samples 4 and 5) and on open-cell natural rubber sponge (sample 8), PUR sheet (unfilled) on closed (sample 26) and open-cell natural rubber sponge (sample 28) and PVC tape on open-cell natural rubber sponge (sample 36).

METHOD OF TESTING

Laboratory ice-adhesion measurements

The shear adhesion of ice to the various surfaces under investigation was measured since this form of loading most closely resembled the loading of ice on rotor blades.

A cube of ice, of side 25.4 mm, into which was frozen a wire rod (1 mm diameter) having a hook on the free end, was bonded to the experimental surface by placing a face of the cube onto the latter and filling the gap with water which was then frozen at -20°C for 20 minutes. It was arranged that the wire insert was parallel with and, as near as possible, 2 mm above the surface under test. The adhesion was measured by attaching a spring balance to the hook and loading to failure whilst the surface was at the temperature of test. A loading rate of about 5 N/s along the axis of the insert was used. Ten measurements were made on different parts of the surface of each sample and the average shear adhesion value noted.

Measurements in the icing chamber

Rime ice was built up on the surface of a supported sample in the arctic chamber at -20°C using a water/compressed air mist spray about 1 m from the sample. The water/air mixture from the spray was adjusted so that the ice formed was not powdery (too little water), yet not so wet that the water ran off the sample before freezing. Rime ice 150 mm thick could be formed in 1 to $1\frac{1}{2}$ hours.

Glaze ice was formed on samples at -20°C using a 60° included

angle solid-cone, fine-water spray. The water was pre-cooled before spraying because it tended otherwise to run off the specimen before freezing; lowering the water flow rate instead of pre-cooling caused icing-up of the spray nozzle.

It was impossible to make satisfactory quantitative measurements of ice adhesion to the samples in the arctic chamber. Therefore, all specimens were subjected to qualitative examination such as judging the ease of prising off glaze ice with a lever or, in the case of rime ice, shaking the stand holding the specimens to see whether the ice would fall off under its own weight.

RESULTS

The shear adhesion of ice to composite coatings having different non-metallic and metallic outer surfaces is given in Tables 1-6, respectively. Table 7 gives results of ice adhesion to PE, or PTFE, films attached to the substrate at the edges only and Table 8 gives the adhesion values on metal strips supported in an open frame. In these tables, the ice adhesion quoted, although expressed in kN/m^2 was measured on an area of 625 mm^2. The shear strength was not necessarily proportional to the area covered by the ice; in general the force per unit area required to remove the ice decreased with increase in area and in some cases this trend was very marked.

DISCUSSION

The results show that the adhesion of ice to all the surfaces examined was greatly reduced when a flexible substrate was present between the surface and the rigid metal backing plate. Comparing different surfaces of like thickness on substrates of the same type and thickness, there was little to choose between the adhesion of ice at $-20^{\circ}C$ to PE and to PTFE, whilst the adhesion to PVC tape was nearly as low. Ice adhered more strongly to PUR and to other rubbers, including silicones, the results of which are not reported here, suggesting that the adhesion increased as the crack propagation properties of these low moduli surfaces decreased (see earlier). However, ice adhesion to metal surfaces was very low when the metal could flex readily, which indicated that the surface flexibility was a more important parameter than relative wettability.

Ice adhesion on PE treated with chlorosulphonic acid was significantly greater than on untreated surfaces: the treatment considerably enhanced the wettability of the PE which doubtless

aided the adhesion by the same mechanism as for PUR above. The surface to be exposed to icing was therefore not allowed to come into contact with acid.

In general an increase in substrate thickness lowered the ice adhesion, although occasionally there was some evidence to the contrary (specimens 24-26). The adhesion was also usually lowered by increasing the softness of the sponge rubber substrate; with one exception (specimen 13), the lowest adhesion of ice on a given surface was obtained when the substrate was an open-cell soft sponge rubber 12.7 mm thick. Increasing the thickness of this rubber lowered the adhesion further (specimens 36 and 37). Thus the adhesion of ice to a surface also depends on thickness and type of substrate and can be lower on a comparatively high energy surface such as stainless steel foil on a thick sponge substrate (specimen 54) than on PTFE, which has a low surface energy, on a thinner, harder substrate (specimen 17).

The adhesion of ice to PE or PTFE specimens, in which the outer surface was attached to the substrate at the edges only, was very low, particularly on PTFE. Ice cubes of side 50 mm dropped off under their own weight from those specimens in the vertical position; the deformation of the outer skin which occurs under a given load on the ice is much greater for these specimens and peeling is more readily induced. An ice-shedding coating of this type has been proposed for application to the front of a helicopter-borne rocket launcher. Ice adhesion was also very low on thin metal strips supported in an open frame which gave further evidence that the ability of a surface to deform readily under a low load and yet have a sufficiently high modulus to propagate a crack was a more important parameter governing ice adhesion than the chemical nature of the surface.

Glaze ice, up to 150 mm thick, completely covering the surfaces of the 600 mm square large flat panels could be removed in one piece, with varying degrees of ease, from all the specimens provided that a crack was first initiated between the ice and the coating. Rime ice could also be removed in large pieces on shaking the stand supporting the panel.

On the basis of the above results an optimum coating for a helicopter rotor blade is partly governed by composite thickness, although precise limits have not been laid down and could vary from helicopter to helicopter. For maximum conformity with the original blade shape, the thinnest commercially available sponge rubber (1.6 mm) was suggested for use as the flexible substrate

material, whilst the rain and sand erosion resistant filled PUR coating, Specification WGPS 240, already used on helicopter blades, was retained for the outer surface. Ice adhesion was less on the composite coating having a PE outer surface (compare specimens 14 and 22), but since this type of coating had relatively poor rain and sand erosion resistance, it was not possible to use it on rotor blades. Nevertheless, ice could be more easily removed from the PUR which had a flexible substrate (specimen 22) than when no substrate was present (specimen 29). This provided further evidence in favour of the suggested composite coating; the latter was proposed for practical trials and is the subject of evaluation on Wessex 5 blades. Trials so far have proved promising.

CONCLUSIONS

The adhesion of ice to a surface is greatly reduced when the surface can flex under low loads yet propagate a crack at the ice/surface interface and this principle, which enables peeling forces to operate, can be used to make ice-shedding coatings which could have several practical applications. Of the specimens examined in the laboratory, the lowest ice adhesion was noted on polytetrafluoroethylene film which was attached to a flexible substrate only at the edges of the specimen. However, there was no significant difference between the ice-shedding properties of polytetrafluoroethylene and polyethylene when these films were bonded to flexible substrates, both shedding ice fairly easily. Springily deformable metals can also shed ice readily. Choice of materials, thickness and degree of attachment of the outer surface to the flexible substrate are governed by the particular application and considerations other than ice-shedding properties.

A coating which may improve the ice-shedding characteristics of helicopter rotor blades has been proposed as a result of promising laboratory tests. The coating utilises inexpensive and readily available materials and provides a basis for full-scale trials and further development. Another type of coating is suitable for protecting a helicopter-borne rocket launcher.

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Table 1

SHEAR ADHESION OF ICE ON CLEAR POLYETHYLENE FILMS ON VARIOUS FLEXIBLE SUBSTRATES

Speci-men number	Poly-ethylene film thickness (mm)	Substrate		Shear adhesion of ice (kN/m^2)
		Type	Thick-ness (mm)	
1	0.13	Closed-cell foamed natural rubber	1.6	14.1
2	0.13	Closed-cell foamed natural rubber	3.2	12.5
3	0.13	Open-cell foamed natural rubber	12.7	6.2
4	0.25	Closed-cell foamed natural rubber	1.6	44.4
5	0.25	Closed-cell foamed natural rubber	3.2	28.9
6	0.25	Closed-cell foamed natural rubber	6.3	26.5
7	0.25	Closed-cell foamed natural rubber	12.7	18.6
8	0.25	Open-cell foamed natural rubber	12.7	7.3
9	0.38	Closed-cell foamed natural rubber	1.6	40.6
10	0.38	Closed-cell foamed natural rubber	3.2	19.9
11	0.38	Closed-cell foamed natural rubber	6.3	20.7
12	0.38	Closed-cell foamed natural rubber	12.7	9.6
13	0.38	Open-cell foamed natural rubber	12.7	13.1
14	0.51	Closed-cell foamed natural rubber	1.6	22.1
15	0.51	Open-cell foamed natural rubber	12.7	8.7
16	0.25	No substrate: bonded directly to backing plate	-	>150

Table 2

SHEAR ADHESION OF ICE ON POLYTETRAFLUOROETHYLENE FILMS ON VARIOUS FLEXIBLE SUBSTRATES

Specimen number	Polytetrafluoroethylene film thickness (mm)	Substrate		Shear adhesion of ice (kN/m^2)
		Type	Thickness (mm)	
17	0.13	Closed-cell foamed natural rubber	1.6	18.6
18	0.13	Open-cell foamed natural rubber	12.7	4.1
19	0.25	Closed-cell foamed natural rubber	1.6	34.1
20	0.25	Open-cell foamed natural rubber	12.7	7.9
21	0.13	No substrate: bonded directly to backing plate	-	>150

Table 3

SHEAR ADHESION OF ICE ON POLYURETHANE SHEET (FILLED AND UNFILLED) ON VARIOUS FLEXIBLE SUBSTRATES

Specimen number	Polyurethane sheet thickness (mm)	Substrate		Shear adhesion of ice (kN/m^2)
		Type	Thickness (mm)	
22	0.64 (filled)	Closed-cell foamed natural rubber	1.6	41.4
23	0.64 (filled)	Open-cell foamed natural rubber	12.7	33.8
24	0.81	Closed-cell foamed natural rubber	1.6	34.5
25	0.81	Closed-cell foamed natural rubber	3.2	37.3
26	0.81	Closed-cell foamed natural rubber	6.3	37.9
27	0.81	Closed-cell foamed natural rubber	12.7	26.2
28	0.81	Open-cell foamed natural rubber	12.7	7.6
29	0.64 (filled)	No substrate: bonded directly to backing plate	-	150
30	0.81	No substrate: bonded directly to backing plate	-	>150

Table 4

SHEAR ADHESION OF ICE ON NYLON 66 FILMS on 1.6 mm THICK CLOSED-CELL FOAMED NATURAL RUBBER SUBSTRATE

Specimen Number	Nylon film thickness (mm)	Shear adhesion of ice (kN/m^2)
31	0.20	20.0
32	0.30	16.0
33	0.51	39.3
34	0.76	22.0
	Any film thickness bonded directly to backing plate	>150

Table 5

SHEAR ADHESION OF ICE ON POLYVINYL CHLORIDE TAPE ON VARIOUS FLEXIBLE SUBSTRATES

Specimen number	Polyvinyl chloride tape thickness (mm)	Substrate		Shear adhesion of ice (kN/m^2)
		Type	Thickness (mm)	
35	0.20	Closed-cell foamed natural rubber	1.6	45.5
36	0.20	Open-cell foamed natural rubber	12.7	8.2
37	0.20	Open-cell foamed natural rubber	25.4	4.4
38	0.20	No substrate: bonded directly to backing plate	-	>150

Table 6

SHEAR ADHESION OF ICE ON METAL FOILS HAVING FLEXIBLE SUBSTRATES

Specimen number	Metal foil		Substrate		Shear adhesion of ice (kN/m^2)
	Type	Thickness (mm)	Sponge natural rubber	Thickness (mm)	
39	Shim steel	0.025	Open-cell	12.7	9.7
40	Shim steel	0.038	Open-cell	12.7	6.9
41	Shim steel	0.051	Open-cell	12.7	19.3
42	Shim steel	0.076	Open-cell	12.7	27.6
43	Shim steel	0.127	Open-cell	12.7	13.8
44	Shim steel	0.025	Closed-cell	1.6	16.5
45	Shim steel	0.076	Closed-cell	1.6	62.0
46	Copper-bronze	0.152	Open-cell	12.7	13.8
47	Phosphor-bronze	0.152	Open-cell	12.7	47.6
48	Phosphor-bronze	0.254	Open-cell	12.7	39.3
49	Beryllium-copper	0.076	Open-cell	12.7	9.7
50	Beryllium-copper	0.102	Open-cell	12.7	23.4
51	Spring steel	0.114	Open-cell	12.7	33.8
52	Spring steel	0.140	Open-cell	12.7	27.6
53	Spring steel	0.178	Open-cell	12.7	22.8
54	Stainless steel	0.025	Open-cell	12.7	7.6
55	Stainless steel	0.025	Closed-cell	1.6	41.4

Table 7

SHEAR ADHESION OF ICE ON POLYETHYLENE OR POLYTETRAFLUOROETHYLENE ATTACHED TO SUBSTRATE AT EDGES ONLY OF TEST PANEL

Specimen number	Outer skin		Shear adhesion of ice when substrate is 12.7 mm thick open-cell sponge natural rubber (kN/m^2)
	Type	Thickness (mm)	
56	Polyethylene	0.25	5.8
57	Polytetrafluoroethylene	0.13	< 1.5
58	Polytetrafluoroethylene	0.25	< 1.5

Table 8

SHEAR ADHESION OF ICE ON METAL FOILS SUPPORTED IN AN OPEN FRAME

Specimen number	Metal foil		Shear adhesion of ice (kN/m^2)
	Type	Thickness (mm)	
59	Shim steel	0.076	2.8
60	Spring steel	0.140	7.6
61	Phosphor-bronze	0.152	8.3

IMPACT ON ICING CONDITIONS ON EMPLOYMENT OF FREE ROCKETS

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SLIDE 1. INTRODUCTION 2.75 TRI-SERVICE PROJECT MANAGER

It is my pleasure to address you today on the impact of icing conditions on the employment of free rockets. In reviewing the agenda for the icing symposium, I found that my presentation was the only one scheduled to specifically approach the icing problem from the position of an agency directly involved in weaponization of the helicopter. Consequently, I have expanded the scope of my presentation to include more general information on the impact of a requirement for a system to operate in icing conditions.

SLIDE 2. IMPACT OF ICING CONDITIONS ON EMPLOYMENT OF FREE ROCKETS

This is an outline of my presentation: reviewing operations in icing from the standpoint of how I can deliver ordnance on target under icing conditions; what the current Army capability and procedures are when icing is encountered; the available equipment which can be adopted to allow operations in icing; additional equipment concepts and interface problems which must be considered; and finally, a summary of the primary points of the presentation.

As a tie-in with those who spoke before me, I would like to review an important point from Dr. Yaggy and LTC Griffith's presentation.

The emphasis given by Dr. Yaggy was flight in icing conditions, and LTC Griffith indicated that one of the "Icing Test Objectives" was to be able to operate safely.

I will be stressing to you, who represent the services, Government, and industry, that these are short of the objective of conducting combat operations under icing conditions. This objective is an even more demanding challenge and is the main thrust of my talk.

SLIDE 3. ARMY HELICOPTER TASKS

When I, as an aviator and gunship pilot, review operations in icing, I must break the jobs that Army helicopters have to perform down into two major task categories: troop movement and resupply; and observation and attack. The general classes of helicopters involved in these two categories are also listed. Within each category we must also address what kind of area in which we are operating. The kind of weather conditions which can be tolerated in a logistic area well may be significantly different when we consider the environment of the battle area. I will address the environment of the battle area in more detail in subsequent slides.

In combating icing conditions, just the low visibility characteristics will be encountered more often than actual icing. BG McMullen, who is the Director of the Air Force A-10 Program, described the parameters under which his aircraft must operate in a recent issue of International Defense Review. His analysis indicates conditions on the continent of Europe to be better than a 1000 foot ceiling and one mile visibility, 85 percent of the time. However, isolating the critical area of Germany, the frequency of icing warnings during the winter months are quite high; a previous paper indicates this to be approximately 55 days. Movements of helicopters from point A. to point B. in the logistics area then would be expected to be prevented for a certain percentage of available time. What is the criticality of this logistics area support during the limited time of ice conditions? The question this raises is, if the helicopters are fully equipped, how much increase in availability can be expected? Do we really want to embark on an extensive program just to increase the availability slightly? Is it really cost effective? It may very well be.

However, being able to operate in the battle area and to add that extra amount of availability may be an entirely different situation. We can't forget that many of the biggest tactical successes were achieved at night or in bad weather. Most recently, in the Arab-Israeli conflict, the initial engagements were essentially completed during the first night; or more appropriate to our subject, in the Battle of the Bulge in World War II, the weather played a large part.

Consideration of these factors requires complete analysis of the whole problem to determine the proper solution.

We cannot expect to resolve all these questions in a short period; however, they must be considered. Again, to approach the problem from the position of someone involved in providing a functional weapons system to the gunship pilot, I will assume that someone else has solved the technical problem of keeping the helicopter in the air, and will primarily address how to assure delivery of ordnance on the target.

SLIDE 4. RIPPLE FIRING AT 2500 METER RANGE, ALTITUDE 50 FEET

This photo was taken from the front seat of a Cobra on a firing run from a range of 2500 meters, at an altitude of 50 feet. This test was performed here in California at the Naval Weapons Center, China Lake. As you can see the conditions are excellent visibility; an area target, with a tank painted international orange as the center aim point.

SLIDE 4A. RIPPLE FIRING AT 4000 METER RANGE, ALTITUDE 200 FEET

This is the same target at 4000 meters, at an altitude of 200 feet. I show these pictures as an illustration of the requirement of Army aviation to stay very low and at extended ranges in order to survive against the sophisticated air defense units expected in a mid-intensity war. The question this introduces is how is the attack helicopter going to survive if he is attacking in low visibility? We have some very real limitations right now while flying nap-of-the-earth in clear conditions!

SLIDE 5. REPRESENTATIVE TARGETS, ARMOR AND SURFACE-TO-AIR MISSILES

Considering the mid-intensity war, we may be attacking personnel targets, but these are the vehicles with which we have to contend. If the air defense units have only visual or optical methods of acquiring targets, then their capability is on a par with the helicopter. However, if radar directed quad 23 units are encountered, their range of acquisition and

effectiveness would result in high attrition rates without coming in visual contact.

SLIDE 6.

This slide shows an artist's conception of an armor array. The massed armor threat is the most sophisticated challenge in the mid-intensity scenario. Defeat of this mix of light and medium armor accompanied by air defense units and personnel is of prime importance when considering the effectiveness of our weapons systems. The capability of rotary wing aircraft weapons system to be effective under adverse weather conditions may be the only way to blunt this kind of spearhead.

FILM CLIP. LOW LEVEL, LOW VISIBILITY IN SNOW

This first film clip illustrates the problem with visibility. Notice the visibility to the tower and tree line and you'll see it get worse.

This test with OH-6 and OH-58 observation helicopters was conducted in Michigan during an investigation into engine flame-outs due to inlet icing conditions. The snowstorm would seem to simulate how the visibility would decrease under icing conditions. The pilot may be able to operate under these conditions in a logistic area to do resupply or reposition missions. However, the battle area could put the aircraft in danger from small arms, Sam missiles and radar directed guns without ever coming into visual contact.

If a gunship pilot has to effectively engage a target under conditions such as these, the aircraft attrition rate could be prohibitively high. The analysis of weather conditions, visibility parameters, and attack scenarios must be balanced against the cost of developing weapon systems which are fully qualified for operations in icing. If a pilot finds himself in this type of situation, the weapons system must be oriented towards fast reaction time so he can shoot and leave.

SLIDE 7. BATTLE AREA OPERATIONS IN ICING CONDITIONS

In order for a gunship to be effective under icing conditions in a battle area in the mid-intensity conflict, these five items must be achieved.

The standard Army flight tactic developed for mid-intensity is nap-of-the-earth flight. Consequently, we are concerned with icing conditions generally at ground level and up to about 50 feet. It may be necessary to pop-up to higher altitude to acquire the target, but the pop-up maneuver will be of very short duration. In the March issue of Aviation Digest, pilots were asked what was the minimum safe altitude for nap-of-the-earth at night. Their answers for mountainous terrain varied from 20 feet for single aircraft with high ambient light to 200 feet for multiple aircraft in low ambient light. Most of the answers were above 50 feet which the user has identified as out of nap-of-the-earth altitude. These, and worse conditions, could be expected under icing conditions.

Within the low-level flight regime, the helicopter must be controllable in these low speed conditions. We are aware of the work that ASTA has done here at Edwards in the investigation of low speed wind sensors to help give the pilot a better idea of what his helicopter is doing. If a pilot, either of necessity or inadvertently, flies into a fog bank or area of very low visibility, he is going to need a good low airspeed readout to tell him what to do next. It may be of great value to know how fast you are going in all three vectors. During a test last summer using a Cobra, rockets were to be fired at 30 knots. Most of the time the pilots said the airspeed indicator read zero when the radar controller was telling them to slow down to 30 knots. A good wind sensor to resolve the aircraft vector is also needed for rocket fire control, and we support the effort in which ASTA has been involved.

Target acquisition also infers visibility. As already described, if a gunship is at low level, with low visibility, he is very vulnerable to small arms ground fire. If you fly high enough to avoid small arms fire, the radar directed antiaircraft is effective. Target acquisition at as long of range as possible is desirable; however, in low visibility, target acquisition may be at very short ranges. Quick reaction time is important in this situation, both to line up and fire as well as firing time until you can break off. With a stores management subsystem, a load of rockets can be fired in about one second. We queried the Air Force about the tactical ceiling and visibility minimums that

they would operate under; however, they would not identify what those might be. Generally, they indicated that depending upon the situation, if the pilot felt he would have enough room to operate that the Air Force would provide close air support. From my experience, close air support was rarely provided in Vietnam when ceilings were below 2500 feet above ground level, except for radar bombing. Referring again to the article on the A-10, they are oriented toward operating at 150 knots air speed with ceiling of 1000 feet and visibility of one mile. The Army experience in Germany indicates that even with this improved support severe problems will exist a good portion of the time without an attack helicopter capability.

Functional weapons systems are naturally essential to defeat and/or suppress a target. I will address how we can keep rocket launchers functional in more detail later in the briefing.

Lastly, as mentioned earlier, the tactics and procedures must be developed to avoid the radar directed air defense, particularly under low visibility. This requirement could establish the need for a radar warning device for operations under icing conditions. An important aspect of this is that the pilot must know more than the fact that he is being acquired and tracked. Acquisition can be at two to three times a systems effective engagement range. Area denial would be imposed over an area many times greater than that commanded by the systems effective range.

SLIDE 8. CURRENT WEAPON EMPLOYMENT TACTICS IN ICING CONDITIONS

Now let's look at what the Army would do today if it encountered icing conditions and wanted to fly a rocket firing mission.

The first tactic is the most obvious and probably the one most often performed. Stay home is also what the Air Force does if they know they are going to be risking aircraft in trying to get under a low ceiling in hills or mountains.

The next tactic is basically to abort the mission if icing is encountered. However, neither of these two tactics accomplish the attack helicopter mission.

Next, if icing is encountered in the battle area and a target of opportunity is encountered, the gunship can expend his stores and get out before he is incapacitated.

Depending on weather conditions, sometimes you can assume that the icing conditions are localized to a particular location and either get through it quickly or avoid the area.

Even IFR rules assume a breakout of an established ceiling with low visibility; you may never see the ground until short final.

SLIDE 9. 7 TUBE LAUNCHER IN ICING CONDITIONS

This is a photo of a 2.75 inch rocket launcher after the icing test done by ASTA in January. As you can see, considerable ice is built-up on the front end of the rockets and pods. We have not done any live firing of iced up rocket pods, but on the basis of similar obstruction experience in Vietnam, we can expect the rocket to stay in the tube and burn. In Vietnam the problem was sand and dirt, converted to a low grade concrete by rain. The accumulation around the rocket prevented the round from launching. A hang fire can either just give the helicopter additional speed, cause severe yaw, and with one launcher configuration a hang fire caused separations of a section of launcher tube. The launcher tube in one case impacted the tail rotor resulting in the rotor and gear box leaving the helicopter. The helicopter was able to land in more or less one piece.

SLIDE 10. ICING OF STORES PYLON

This is the wing stores pylon with a considerable build-up of ice. Emergency jettison characteristics could be significantly altered by the ice accumulation and this aspect also needs to be tested. The ice on the out-board pod is what could be expected with a flat protective cover.

SLIDE 11. STANDARD ARMY LAUNCHERS

In this section of the presentation, I want to go into some hardware which could be made available for further rocket system tests under icing conditions. In order to

do this, this photo shows the two types of 2.75 inch rocket launchers which are currently in the standard inventory. The M200A1 19 round launcher is on the in-board station and the M158A1 7 round launcher is on the out-board station. The M158A1 is the launcher involved in the aircraft incident I mentioned earlier, and you can see why, the tubes are exposed and held together by two fixtures. These launchers are loaded with the standard rocket with a 10 pound warhead. The nose of the rocket fuze sits well back into the launcher tube. Now you can see more clearly why sand and dirt would accumulate around a rocket as the armed gunship sits next to a dusty landing pad. We also have a 17 pound warhead, and in this case, the rocket fuze and a portion of the warhead are exposed in front of the launcher bulkhead. These rockets would also be expected to accumulate ice between the rocket and launcher, resulting in potential hang fires.

SLIDE 12. TUBE CLOSURE FIXTURES

In order to prevent the hang fire problem in the 7 tube launcher, our office investigated a number of methods to prevent the accumulation of dirt in the front of loaded launchers. The most promising method of combating the problem turned out to be this commercial cap-plug. It fits snugly in the launcher tube and since it is injection molded plastic, the cost is only a few cents per rocket.

SLIDE 13. 158 LAUNCHER WITH CAPS

This is a photo of the 7 tube launcher with cap-plugs installed. The caps satisfied the need to keep sand out of the launcher tubes. However, with the reduction in American involvement in Southeast Asia, the cap-plugs were never fielded as a stock item.

SLIDE 13A. M200 WITH CAP-PLUGS

The cap-plug could be used in the icing environment. However, no tests have been conducted on the effect of firing a rocket which has to push out not only the cap-plug, but also break the ice buildup.

FILM CLIP. FIRINGS FROM LAUNCHERS UTILIZING CAP-PLUGS

This film clip shows the rockets being fired through the cap-plugs from a Cobra at Fort Rucker. You will notice that with this cap-plug design a single rocket launching may eject more than one plug. We don't know what the characteristics would be under icing conditions.

Foreign object damage problem is the next item to consider. You can see how the cap-plugs, even though they are ejected below the Cobra wing, end up going past the tail rotor. The chunks of ice built-up on the launchers could do the same thing during rocket firing or launcher jettison. We do not have any data on what ice chunks do to tail rotors, but it could be disastrous.

SLIDE 14. FRANGIBLE FAIRINGS

These Air Force launcher fairings also fit on the standard Army 19 tube launcher. The forward, streamlined fairing is made of frangible fiber material with an aluminum ring for attachment to the launcher. The aft fairing shown here is also frangible material. The frangible closed fairing can also be used on the aft end of the launcher.

SLIDE 15. FAIRINGS INSTALLED ON LAUNCHER

Enclosing the launcher with fairings should work in the icing environment; however, the first rocket firing will destroy the protective cover. As with the cap-plugs, no tests have been performed to determine how the frangible fairings would stand up with a thick coat of ice or how firing the rocket through an ice-encrusted fairing will affect the rocket fuze. We might have to develop a ballistic fairing which would have a small explosive change to jettison the fairing prior to firing.

FILM CLIP. EJECTION OF FAIRING UPON FIRING

The next film clip shows how the frangible fairing is ejected during rocket firing from a fixed wing aircraft. You will notice the fairing being ejected more or less in one piece.

At high airspeeds the fairing then breaks up into small pieces; however, we don't know what would happen with a low speed helicopter and an iced-up fairing.

SLIDE 16. ROCKET ICING QUALIFICATION TESTS

If the 2.75 Inch Rocket System is to be qualified for operations under icing conditions, these tests would have to be performed. The static tests could be performed on the ground first, to verify that hang fires would occur and then firing, or simulated firing through the covers. To determine the effect of the ice on the cover, the various rocket configurations would have to be tested first with just the cover and then with various thicknesses of ice to determine the limits of performance. The rocket design, specifically the fuzes, may have to be changed to withstand the icing launch environment.

Once the safety tests have been performed on the ground, airborne icing tests would have to be conducted. These airborne jettison and live firings could be quite extensive to prove that there is not a safety hazard.

The ejection of launch covers, including large pieces of ice, may also affect the qualification of a system because of foreign object damage. We have experienced major damage to a tail rotor with a portion of the launcher tube, so the same problem could occur with ice.

SLIDE 17. XM227 LAUNCHER

Moving into the area of equipment concepts, there are new developments in the 2.75 Inch Rocket System which may complicate, and some of which may help to solve the problem operations in icing.

This slide shows the XM227 launcher which has been undergoing development as part of a remote set fuzing subsystem. You can see the umbilical cable which connects each fuzed warhead with the launcher and subsequently to the electronic fuzing subsystem aboard the helicopter. Shown is both the 10 and 17 pound HE warhead with the XM433 fuze which can be electronically set by the pilot for super-quick, forest penetration as bunker delay while in flight. Also shown are the XM255 flechette warheads which can also

be electronically set by the pilot for airburst from 500 to 4000 meters from the helicopter.

When we think about icing, this functional concept gives us a number of problems. In the current configuration the umbilical is going to be in the way. The long warheads are going to stick out of the front of the launcher. The plastic nose of the flechette warhead and the probe on the forest penetration fuze may have trouble when trying to break through a fairing covered with ice.

SLIDE 18. PACK LAUNCHER AND HARDBACK ASSEMBLY

This picture shows the use of a concept for rapid rearm called the pack launcher. A boresighted hardback is attached to the stores pylon, and by means of a special launcher and winch, one man can put a fully-loaded launcher into position. This concept was developed for the Army's forward area refuel and rearm point, FARRP for short. Since the concept is for the launcher to also act as a shipping container for the rockets, this could lend itself to some of the solutions to the icing problem.

SLIDE 19. FOAM DIAPHRAGM

This is a picture of a foam diaphragm for a 19 tube launcher to protect the rockets until the moment of firing. This kind of diaphragm could be built into the pack launcher so that as the launcher is loaded at the rocket assembly plant, the diaphragms are put into place to protect the rocket regardless of whether the concern is ice or dirt.

SLIDE 20. FOAM DIAPHRAGM, INSTALLED

This is another configuration of the foam diaphragm. The cover would have to be strong enough to withstand casual damage and rocket back blast, yet be frangible so as to not damage the rocket when it is fired.

SLIDE 21. ROCKET EQUIPMENT CONCEPTS

To summarize the rocket equipment concepts which could be used in the icing environment, the basic task is to cover the launcher tubes. The best way to do that has not been determined. We have frangible and reusable

fairings for the 19 tube launcher. The Army 7 tube launcher currently has no provision for fairings, although the Air Force does have them that size. Currently, the 7 tube launcher would have to depend upon individual tube covers and that may be the best way to protect the 19 tube launcher as well.

Probably the best alternate technique would be to enclose the launcher tubes with frangible disks.

As with the current inventory, the new rocket designs would have to be evaluated on the basis of how they would perform when tested under icing conditions.

SLIDE 22. COBRA PIP PROGRAMS

In further investigation of the interface impact of equipping the helicopter for operating in icing, we also must consider how much weight will be added. The first section of this slide shows a weight chart for a standard Cobra and TOW Cobra. Then the ammunition and launchers are added. In both cases, the user doesn't want to put any more weight on either aircraft. However, the Cobra office has approved PIP programs which would add another 100 pounds to each model. This does not include any weight for stores management, fire control, or remote set fuzing which should be added to the AH-1G. Beyond either of these is the Product Manager for aircraft survivability equipment who could add another 175 pounds. It remains to be seen what anti-icing equipment will add. The degraded performance of the aircraft in moderate icing conditions must also be defined. A major goal of everyone associated with the attack helicopters is to keep the additional weight as low as possible.

SLIDE 23. ICING QUALIFICATION

As the final section of the development of equipment concepts, I want to discuss the ramifications of icing as a requirement. To be serious about attaining the ability to go into a battle area under icing conditions, we must equip the aircraft not only to fly from one point to another under low visibility conditions, but also to allow it to survive and attack. Image enhancement, such as low light level TV, infrared, low air speed sensor, fire control, a radar warning system, all fall into this category.

Next, if icing qualification is to be a serious requirement, it must be specifically addressed in the weapon required operational capability document.

Icing must then be specifically addressed when a weapon system is in advanced and engineering development. It's too late for a system that is in the inventory; the best we can do is go back and patch up as necessary. If icing qualification is going to impact on the acceptance of a system by the user, then any new weapon idea now in development must be re-oriented to determine how it is going to work in ice.

Lastly, the TECOM tests that develop the data on which a system is accepted must also address how it will perform in ice. Right now we have the electronic remote set fuzing system in DT II. We are testing at cold temperatures, but not under icing conditions. TECOM would be more likely to perform this kind of qualification test than one of the TRADOC agencies in operational tests.

SLIDE 24. IMPACT OF ICING ON WEAPONS EMPLOYMENT

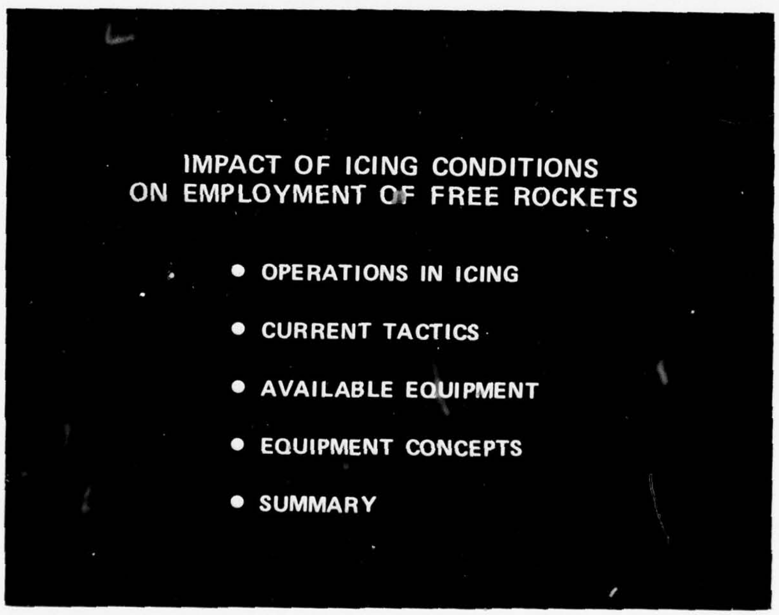
To summarize the presentation:

To operate in a battle area under icing conditions with a functional weapons system, and with effectiveness, will require specialized equipment. The analysis of a system must address whether every system has to be qualified for icing operations regardless of what part of the world it is going to be used, and whether that system even if it is qualified for icing, could be used effectively.

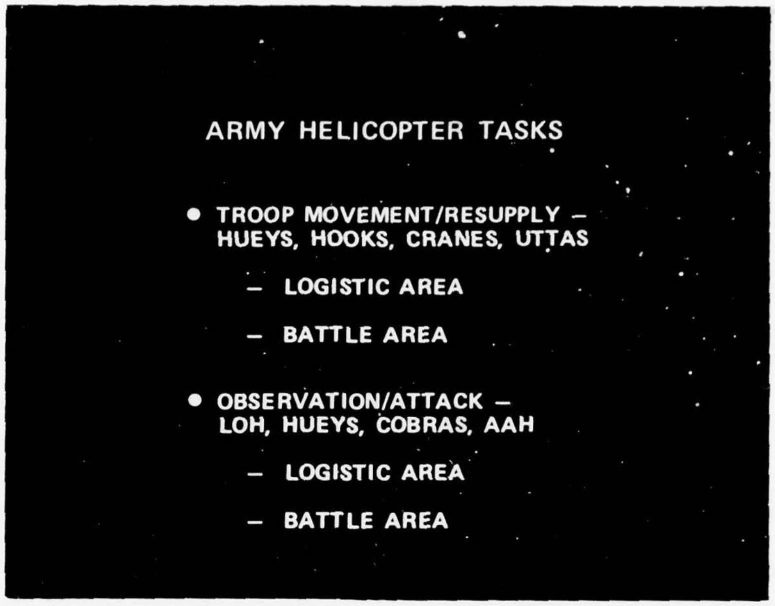
The current tactics and equipment have not been designed for optimum performance under icing conditions. We are basically at the mercy of the weather, and we operate around it, not in it. This is our real challenge for increased operational effectiveness.

In the category of available equipment, we do have some preventative measures which could be used; however, quite a number of tests would be necessary to determine what part of the Army's 2.75 inch rocket inventory could be considered as icing qualified.

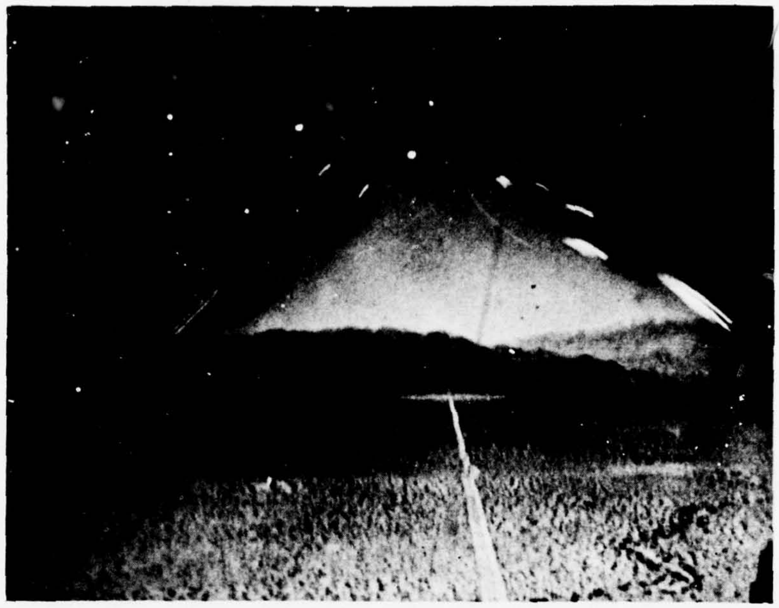
Finally, we are in the midst of defining how the next generation of free flight rocket systems are going to perform. If icing is to be enforced as a crucial requirement, then the development plans and test plans will have to reflect that requirement and the additional test and development costs will have to be integrated into the system budget.



Slides 1 and 2.



Slides 3 and 4



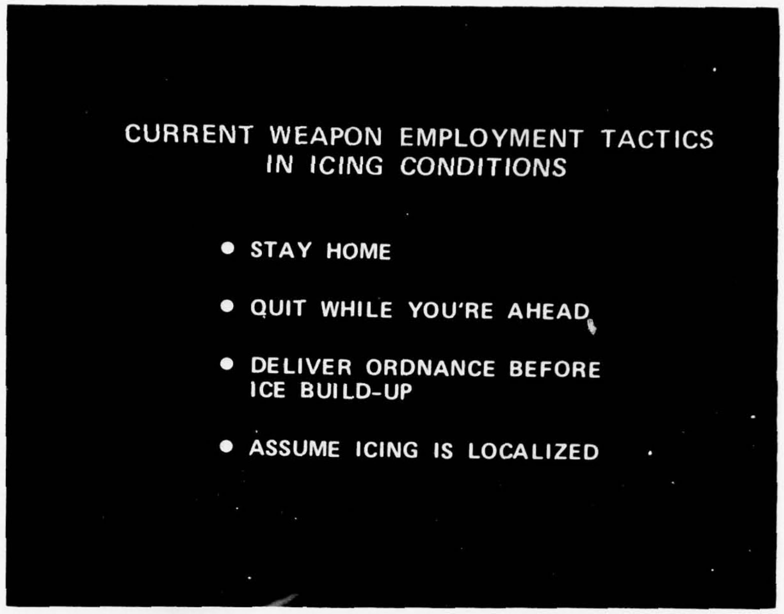
Slide 4A.

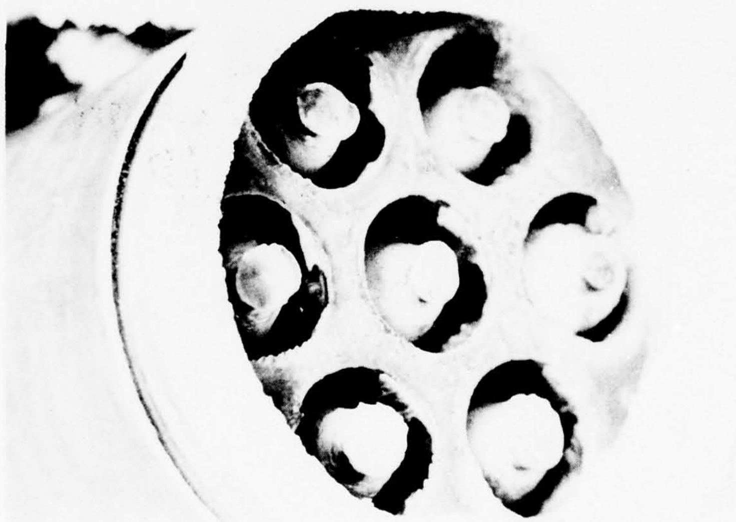
Slide 5 is being deleted from this summary due to its classified nature.

BATTLE AREA OPERATIONS
IN ICING CONDITIONS

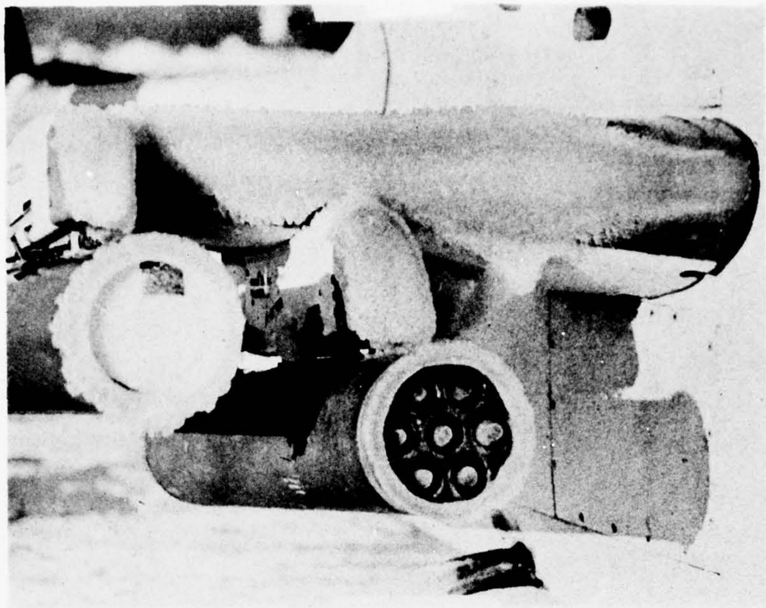
- LOW LEVEL FLIGHT
- CONTROL HELICOPTER AT LOW AIR SPEEDS
- ACQUIRE TARGET IN ADVERSE WEATHER
- FUNCTIONAL WEAPONS SYSTEMS
- AVOID RADAR DIRECTED AIR DEFENSE

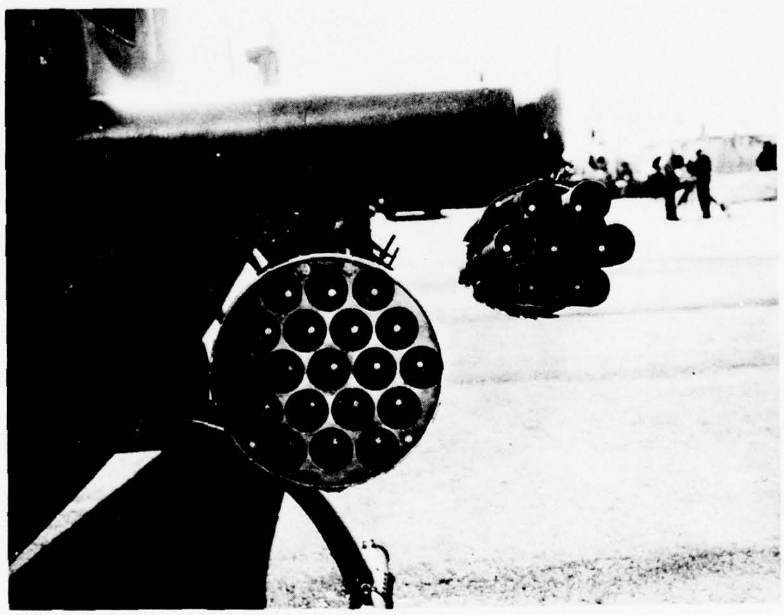
Slides 6 and 7.





Slides 8 and 9.





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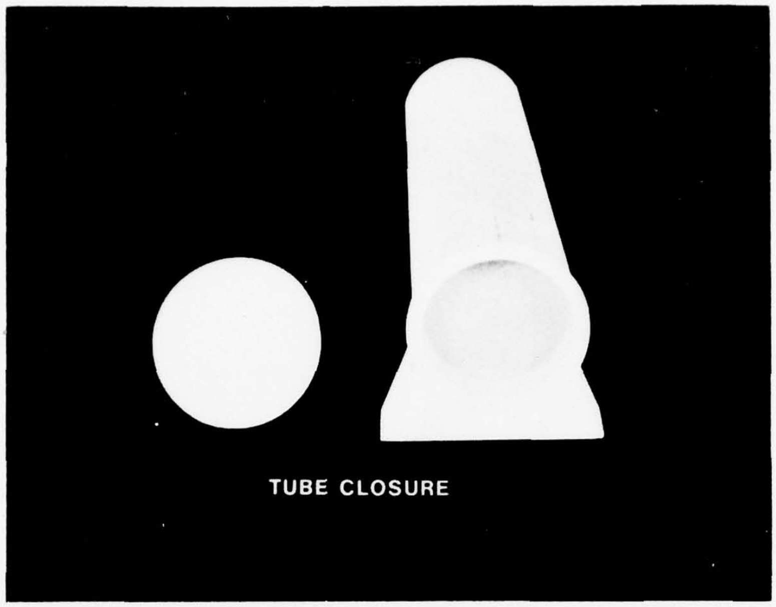
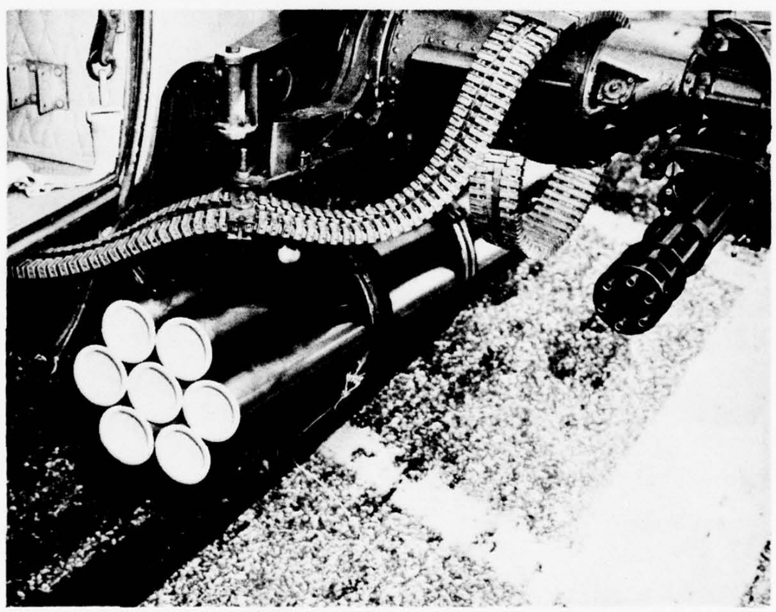
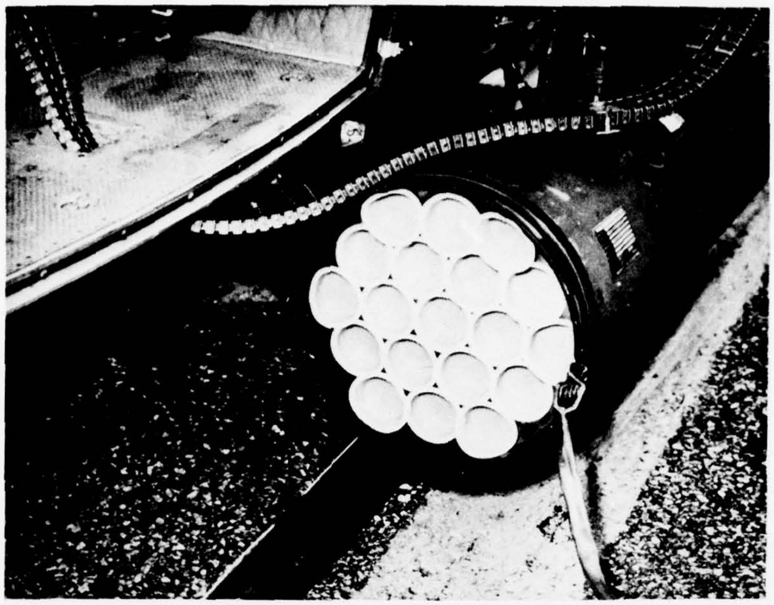
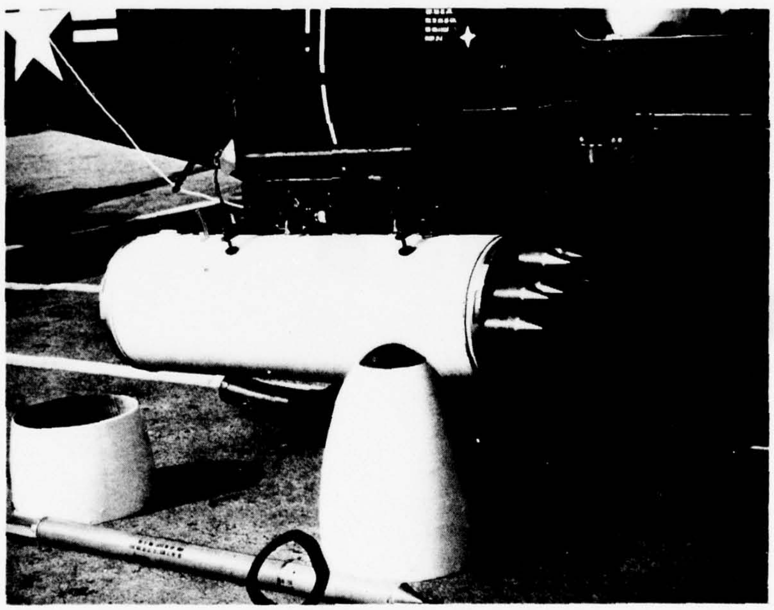


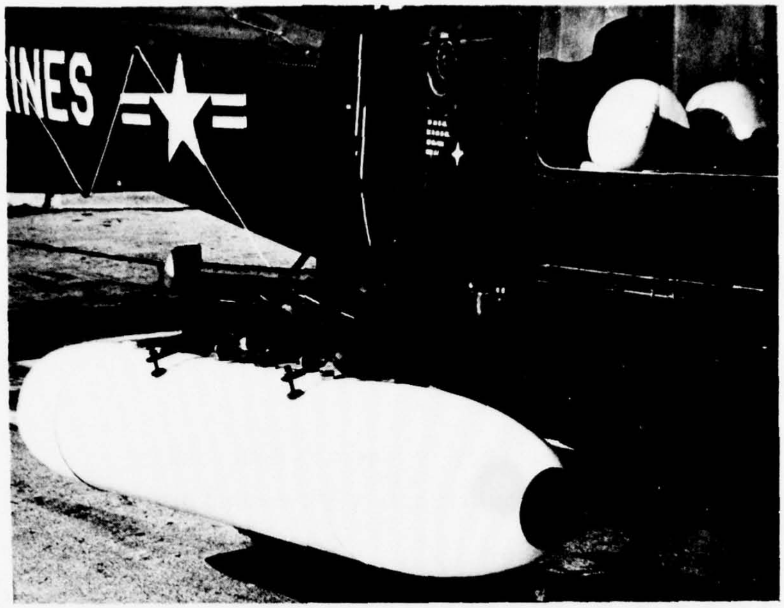


Slides 12 and 13.





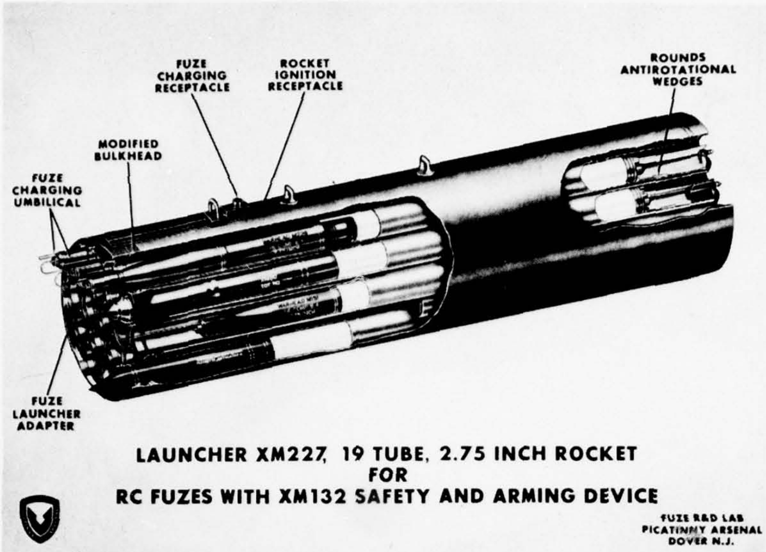
Slides 13A and 14.



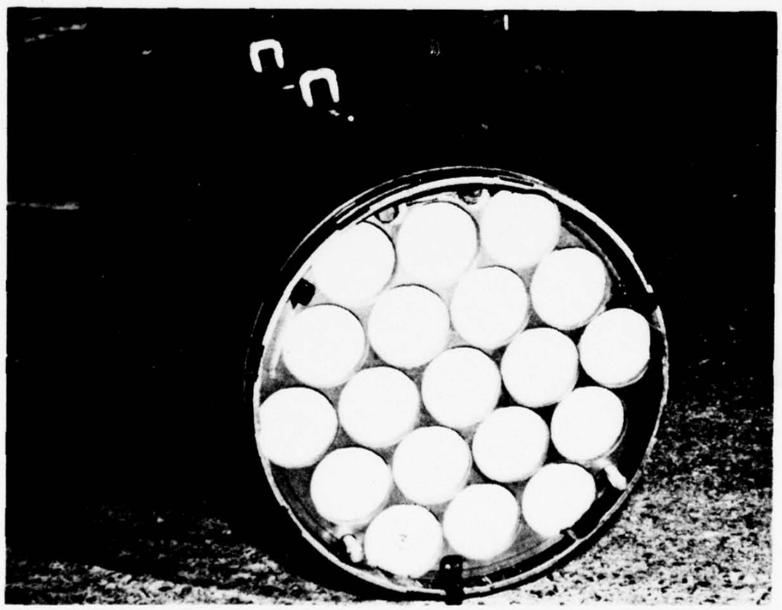
ROCKET ICING QUALIFICATION TESTS

- STATIC TESTS
  - VERIFY CURRENT PROBLEMS
  - FIRE THROUGH COVERS
    WITHOUT ICE
    WITH ICE BUILD-UP
  - IMPACT ON ROCKET DESIGN
- AIRBORNE TESTS WITH ICING
  - JETTISON
  - LIVE FIRING
  - FOREIGN OBJECT DAMAGE (FOD)

Slides 15 and 16.



Slides 17 and 18.



Slides 19 and 20.

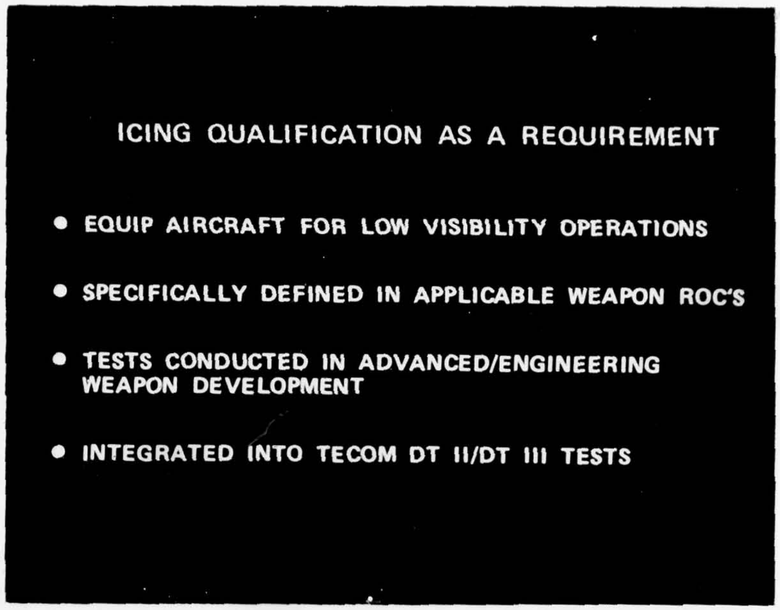
ROCKET EQUIPMENT CONCEPTS

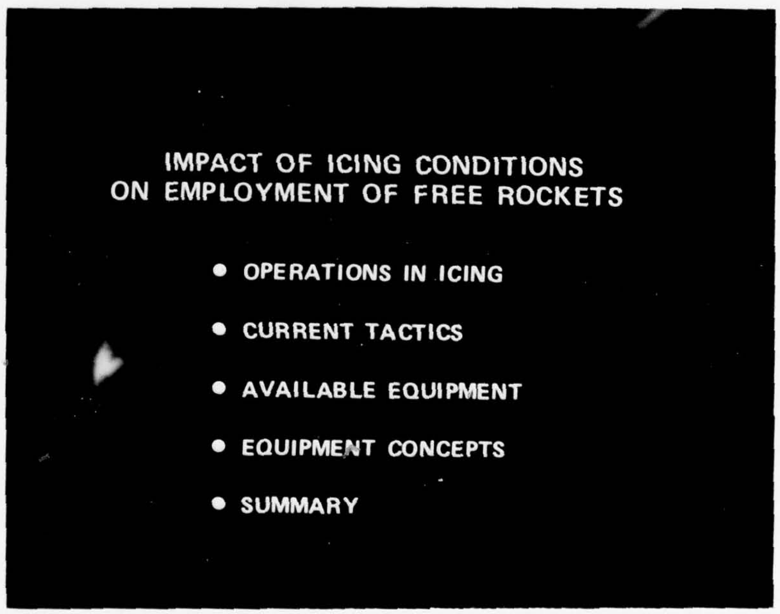
- COVER LAUNCHER TUBES
  - FRANGIBLE FORE AND AFT FAIRINGS
  - FRANGIBLE FORE, REUSABLE AFT FAIRINGS
  - INDIVIDUAL TUBE COVERS
  - FRANGIBLE DISCS BUILT INTO PACK LAUNCHER
- INTERFACE TESTS
  - FIRE THROUGH COVERS
  - IMPACT ON ROCKET DESIGN

AH–1 COBRA AND APPROVED PIP PROGRAMS

ITEM	AH-1G (POUNDS)	AH-1Q (POUNDS)
AIRCRAFT	5760	6230
CREW AND FLUIDS	465	465
FUEL (1 HR +)	800	800
STORES PYLONS	100	80
FLYAWAY TOTAL	7125	7575
ARMAMENT	2440	980
PIP		
FEATHERING AXIS BEARING	42	42
INSTRUMENT FLIGHT SYSTEM	15	15
BALLISTIC CANOPY	15	15
ARC 114 RADIO	12	12
MISCELLANEOUS	16	16
TOTAL PIP	100	100

Slides 21 and 22.





Slides 23 and 24.

HELICOPTER ICE DETECTION SYSTEMS

by: David Grant

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YEOVIL, SOMERSET, ENGLAND

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Educated at Southall College of Technology, London, Department of Electronic Engineering. He has had 16 years experience in electronic research and development and for the past 8 years has been concerned exclusively with Atmospheric Data Sensing Devices.

Abstract

The experience gained during development and flight testing of ice detectors and outside Air Temperature indicator systems on helicopters during the past 5 winters is discussed in detail. The paper also describes a new accretion type of detector which is extremely versatile in its application.

INFERENTIAL ICE DETECTOR SYSTEM

Introduction

The requirement for a reliable ice detector system for helicopter application is widely recognised, particularly by the armed services who may have to operate in icing conditions. A considerable amount of testing of the various types of detector available has taken place in recent years and is likely to continue as a number of problems remain to be overcome. The inferential ice detector has been fitted to a number of helicopters in winter icing trials by several armed services and helicopter airframe manufacturers since 1968.

System Description

The theory and principle of operation of this system has been described in detail elsewhere (ref. 1) and so only a simple description will be given. The system has three component parts (see Figure 1) -

(1) A Moisture/Temperature Sensing Head.

(2) A Control Module.

(3) An icing severity or rate indicator.

(4) An ice accretion indicator system (optional fit).

The Moisture/Temperature Sensing Head consists of two cylindrical heater/sensor probes mounted on a short aerofoil section mast. The front heater is exposed directly to the airflow and impinging water droplets and the rear heater is contained within an inertial separator which removes any water droplets from the airflow over it's surface (see Figure 2).
Both heaters are maintained at a constant temperature (approximately 150°C) by the electronic control module. The physical proportions of the probes and the recovery factor of the inertial separator give equal cooling to

the two probes under dry air conditons and therefore the same electrical power is required by each heater.

When supercooled water droplets are present in the airstream the front probe is cooled and its heater draws increased power to maintain temperature equality with the rear probe. The difference in power levels between the front and rear probe is therefore a fraction of the amount of water evaporated from the front probe in unit time. This power difference is processed by the electronic control module and presented on the indicator in terms of liquid water catch rate.

The icing surface temperature is obtained indirectly by a temperature sensor which is part of a control loop maintaining the sensing head support mast at a temperature set a little above freezing point. This temperature signal is also used to inhibit the indicator above the temperature at which no ice can form.

An additional output facility is provided from the control module for an ice warning lamp and control purposes if required.

Ice Accretion Measurement

It is desirable to relate the maximum potential icing severity or rate indication of the inferential ice detector to an indication of total ice build during an icing encounter.

Such a system was fitted to several trials aircraft and operates by time integration of the analogue icing severity indication given by the 0 - 2 grm/m^3 scaled indicator of the detector system.

In general terms, a free water concentration of 2 grm/m^3 at 90 knots is approximately equivalent to an icing rate of 6 mm/min. By means of voltage to frequency conversion, a digital indicator is arranged to give a count of 600 per minute for full scale deflection of the icing severity indicator and pro-rata for lower amounts.

Calibration

All ice detector systems are calibrated in the icing wind tunnel, (see Figure 3).

Calibration of the Wind Tunnel is carried out using an assembly which is substituted for the test area, (see Figure 4). The apparatus consists of a motor driven rotating rod which is mounted horizontally in the working section of the tunnel in place of the normal test item.

The probe is illuminated from above and a magnified image is projected onto a ground glass screen. The probe is cooled by a supply of carbon dioxide gas.

By measurement of the time taken for the probe to increase its diameter by a known amount due to ice accretion, the tunnel airstream water content may be estimated. The initial probe diamter is 0·031 inches and the build diameter used is 0·059 inches.

Helicopter Installation

The selection of a suitable mounting position for the ice detector sensing head must take into account the following considerations:-

(1) Correlation of the icing severity or rate indication with ice build on critical aircraft surfaces, e.g. Rotor Blades.

(2) The free water impinging on the sensing element should not be reduced by disturbed airflow or from ice accretion on aircraft surfaces forward of the sensor.

(3) Positioning of the sensor such that the airflow over it is as laminar and unidirectional as possible.

The third criterion is the most difficult to achieve due to the inherent manoeuvrability capability of the helicopter and its downwash.

Correct operation of the inertial separator, which is part of the moisture sensing head previously described, requires an airflow condition over it which is laminar and has pitch and yaw components not exceeding $\pm 5^{\circ}$. Operation outside these limits, which has arisen on helicopter installations upsets the cooling balance between the two sensing probes of the moisture sensing head and results in false ice warning signals being given.

Taking the Wessex 5 helicopter as an installation example the sensing head was initially mounted on the upper side of the nose of the helicopter. This proved completely unsatisfactory as spurious icing signals were given over most of the flight envelope.

The sensor was subsequently relocated on a platform under the fuselage immediately beneath the cabin door. This gave some improvement as the rotor downwash component was reduced but any deviation from level flight still produced spurious signals. A few flight tests with streamers fitted near the sensor were made which confirmed the varying flow patterns.

The sensor, still located as previously, was now fitted with a short box section to act as a shield and make the airflow direction more uniform.

With the further reduction of the false ice warning signals it now became evident that the detector system was not always giving an indication when light icing conditions were encountered due to possible interference from the nose intake and its bleed air system. Further trouble was experienced from the liquid anti-icing system being tested on the intake, the sensor being coated with a fine spray of the fluid.

The sensor and shield were relocated on the undercarriage wheel arch during last winter's trial. Results have been encouraging but the spurious ice warning signal problem remains. Some development work to overcome this problem has been carried out since the trial and a modification to the sensor involving the mounting of director plates alongside the inertial separator (see Figure 5) has been tested in the wind tunnel. The results are very promising, the spurious signal error due to pitch and yaw variation being reduced to about 5% of its original value.

Arrangements are in hand to flight test the effect of the modification during the summer months.

Other Installations

The ice detector system has also been fitted to the Sea King and BO 105 helicopters during the last winters trials. Installations on both of these aircraft was beneath the fuselage. The detector has, on earlier trials, been fitted to a Sikorsky S61, operated by British Airways Helicopters.

Ice Detector Operation in the hover mode

For normal forward flight icing, in a simplified form, is the product of airspeed x liquid water content = catch. A helicopter can however be subject to icing conditions in the hover, the rotor blades and engine intakes being the most critical areas.

Since it is not normally possible to site an ice detector in these positions provision for creating an adequate airflow over the sensor of moisture laden air is desirable.

In order to achieve this the ice detector sensor has been fitted in a jet pump arrangement powered by engine bleed air, (see Figure 6). Such a unit has been mounted on a Sea King helicopter during last winters icing trial.

Tests have shown that the sensor is affected by bleed air pressure variations during flight, and the cause is considered to be due to the bleed air annulus being too close to the inertial separator of the sensor. Some modification work to improve the performance is proposed. The installation of the ice detector on the S61, is exceptional in that the sensor is mounted on the pitot bracket sited above the rotor blades. Not only is it possible to measure icing in the hover condition, but also to correlate the rotor icing condition with the indicated icing severity more accurately.

Test Results

A typical set of result obtained on a Wessex 5 furing tests at Ottawa, Canada, last winter is shown in Figure 7.

The liquid water concentration indicator was calibrated to give a full scale deflection of 2 grm/m^3 at an airspeed of 90 knots. An ice collecting rod (Hot Rod) was mounted in view of the second pilot and used to assess the ice build up.

The immediate response of the ice detector system to the entry into icing conditions can be seen, the ringed line giving the maximum potential icing rate calculated from the result.

The 'hot Rod' accretion rate is lower than the potential rate as would be expected. The ice accretion counter was in course of adjustment in order to match its reading to the 'hot rod', but its operation is reasonably successful.

Some false signals occur at 140-160 seconds and 240-260 seconds due to aircraft manoeuvring below the icing cloud base. The signals around 20 seconds occurred during lift off.

All readings with the exception of the hot rod were derived from film records of the instrument panel taken every 10 seconds. A considerable amount of information from other flights still remains to be evaluated.

ACCRETION TYPE ICE DETECTOR SYSTEMS

Fuselage Mounted Type

Accretion type detectors are available in a variety of forms, the types being most currently used for helicopter evaluation being the vibrating rod, radiation and visual ice accretion rod (Hot Rod). The latter has been used extensively during winter icing trials as a primary reference for comparison with ice build upon the helicopter critical surfaces. As a visual device it is mounted in view of the pilot and can be fitted with a collar or ring in order to estimate the ice build. It is of aerofoil section and contains a heater to enable periodic dispersion of the ice build and by this means an assessment of the icing rate can be made.

With the increasing instrumentation fitted to modern aircraft the tasks of the pilot become more demanding and the need to make frequent observations of the 'Hot Rod' in case an icing encounter occurs therefore imposes an additional burden.

It was therefore seen that if the 'Hot Rod' could be modified to give a warning signal close to the onset of icing conditions then this would be a valuable improvement.

Methods of detection using infra red radiation have been known for many years, but its potential has never been exploited fully due to problems with the optical arrangements required. With the advent of sub-miniature infra red emitters and detectors, primarily developed for computer tape and punched card readers but extremely rugged in construction, the detection of icing conditions by this method has become practical.

For the past two winters, a modified 'Hot Rod' with the photo electric devices mounted on the leading edge of the aerofoil, has been evaluated on two helicopters, a Sea King and Puma. Tests on the aircraft and in the icing tunnel have established that an ice warning signal is given when the ice build between the sensors reaches approximately 0·5 mm. The unit is about to be developed to a pre-production standard and is at present scheduled for fitment to a Lynx helicopter which will be undergoing icing trials in Denmark this coming winter.

As mentioned previously the unit is an adaption of the standard Hot Rod now fitted to many service Helicopters. Direct substitution is therefore possible, the only additional wiring being an ice warning indicator lamp.

Development of a more sophisticated accretion type detector is proposed such that an airflow inducer system may be incorporated for measurement in the hover or at low forward airspeed. An additional feature not found in present detectors of the same type will be control of the icing surface temperature.

This will be limited at the upper temperature in order to prevent excessive temperature build up which will affect successive ice accretion and to prevent damage to the photo electric devices. Ice warning signals will be inhibited until the icing surface temperature is below the no icing temperature. This will reduce or eliminate the possibility of false warning signals due to dirt, insects, etc., which could cause mat failure at high ambient temperature in an integrated system.

Rotor Blade Type

Measurement of ice accretion on rotor blades has not previously been practical due primarily to the physical dimensions of the ice detector

sensor. The sub-miniature photo electric devices mentioned previously have been incorporated in a new type of sensor which is of extremely small size, which when mounted on the icing surface virtually becomes part of it. The sensor is shown in Figure 8.

The photo electric devices are bonded to a flexible substrate containing a heater element which can be energised either manually or automatically to remove ice build between the sensors. The sensor is designed for attachment by bonding in a similar manner to strain gauge instrumentation. The detector is connected to its control box by four wires of relatively low current capacity. The control box which is about the size of a cigarette package could feasibly be mounted on the rotor head to reduce the slip ring connection to one or two leads if 28 V is already available through the rings.

By series connection of the light sources and parallel connection of the photo electric detectors a number of ice detector units may be connected to a single control box. Ice build upon any detector unit will then produce a warning signal.

The sensor may also be used to detect freezing rain deposits which normally occur on the upper side of horizontal aircraft surfaces.

OUTSIDE AIR TEMPERATURE MEASUREMENT

Measurement of true outside air temperature under icing conditions is an essential requirement when considering the ice shedding characteristics of a helicopter. The combination effects of icing, airspeed and altitude require that a correction to be applied in order to achieve a reasonable accuracy. The correction applied evaluates the ram temperature rise (Δt) and depends upon the recovery factor (α) of the measuring instrument and the true velocity of the aircraft.

At relatively low airspeeds, such as are applicable to helicopters the ram temperature rise is low. Thus providing the recovery factor of the thermometer is also low, then readings with sufficient accuracy can be obtained directly by using a shielded type of thermometer. The inertial separator design which is used in the inferential ice detector system described earlier has a ratio of internal airstream velocity to free stream velocity of approximately 0·3. This has been verified by wind tunnel testing using a hot wire anemometer.

The recovery factor for thermometers mounted in this type of housing is approximately 0·75 over the airspeed range up to 200 knots. Therefore the temperature indicated by the probe Ti following the relationship -

$$Ti = Toat + 0{\cdot}75 \left(\frac{0{\cdot}3\,V}{100}\right)^2$$

$$= Toat + 0\ 0675 \left(\frac{V}{100}\right)^2$$

TOAT is the true static temperature and the term in the bracket is the ram temperature rise. At low airspeeds this term (Δt) is low. Therefore Ti is almost equal to Toat, the error being less than 0·5°C over the airspeed range for a helicopter. The equilibrium surface temperature of the

probe for various conditions is shown in Figure 9. Reference 2 gives useful additional information.

The use of an inertial separator with the thermometer probe imparts two advantages over supposedly straightforward temperature measuring devices.

(1) Ice build upon the temperature measuring surface is eliminated and therefore errors due to stagnation are avoided.

(2) The effective air velocity over the thermometer surface is low in relation to the free stream velocity, resulting in negligible error due to kinetic heating up to about 200 knots.

The OAT indicator system is shown in Figure 10.

The temperature sensing head consists of a platinum resistance thermometer housed within an inertial separator body. The action of this in precluding any free water droplets has been described previously. The temperature sensor is connected to an electronic amplifier contained within the sensing head boundary layer mast. A particular feature of the electronic amplifier circuit is that a very low voltage is applied to the temperature sensor element resulting in negligible self heating.

Testing of the systems is to continue, some problems with electrical insulation breakdown in previous trials having marred the performance of the instrument. A modified unit with improved construction and calibration is now available. It is scheduled for installation on the Lynx helicopter for the next winter icing trial.

CONCLUSIONS

In summarising the present state of the art regarding ice detectors and OAT indicators the writers opinion based upon development and trials experience is as follows -

Inferential Ice Detector

This detector is capable of measuring the onset of liquid water droplet impingement on the airframe and as such should give the earliest ice warning indication.

The instrument, however, in its present stage of development is sensitive to airflow conditions in the region of the sensor and requires careful attention to the system power supply wiring.

The performance improvements obtained with the sensor mounted in a duct and containing airflow director plates are such that this arrangement is recommended for helicopter installation.

Ice Accretion Type Detectors

In the writer's opinion the only satisfactory accretion type detector is one which can be mounted upon and become an integral part of the critical icing surface.

Present airframe mounted ice accretion detectors appear to work when in medium to low freezing temperatures at moderate icing rates, approximately 1 - 4 mm/min. At high accretion rates the cycle time of the de-icing heater is long and the icing surface characteristic becomes affected due to the thermal time constant of the surface. At temperatures just below freezing low icing rates go undetected due to latent heating effects upon the icing surface.

The 'Hot Rod' accretion type detector used purely as an ice warning indicator and using manual de-icing heater appears to be the best compromise so far obtainable.

OAT Indicator Systems

The bi-metal or 'meat' temperature thermometer has been used for helicopter OAT measurement for many years and from its simplicity gives the appearance of being reliable. It does however suffer from two principle defects when used in icing conditions.

(1) The temperature sensing element will read the stagnation temperature when ice build upon it occurs.

(2) The accuracy of the instrument is considerably affected by the temperature difference between the indicator dial and the temperature sensing surface.

The development of electrical OAT indicator systems has met with a number of problems, the higher accuracy and more flexible installation causing other problems.

A principle problem is susceptibility to engine exhaust gas or bleed air outlets, the changing flow pattern from these over the flight envelope producing variations in indicators from sensors mounted in different airframe positions.

In general some further trials work with these instruments is required, also the wider temperature range now required whilst maintaining the high accuracy required ($\pm$ 0.5°C) makes a digital temperature indication essential.

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ROTARY WING ICING SYMPOSIUM. SUMMARY REPORT. VOLUME II.(U)
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2. B.L. Messenger. Equilibrium Temperature Of An Unheated Icing Surface As A Function Of Airspeed. Journal of Aeronautical Sciences, January, 1953.

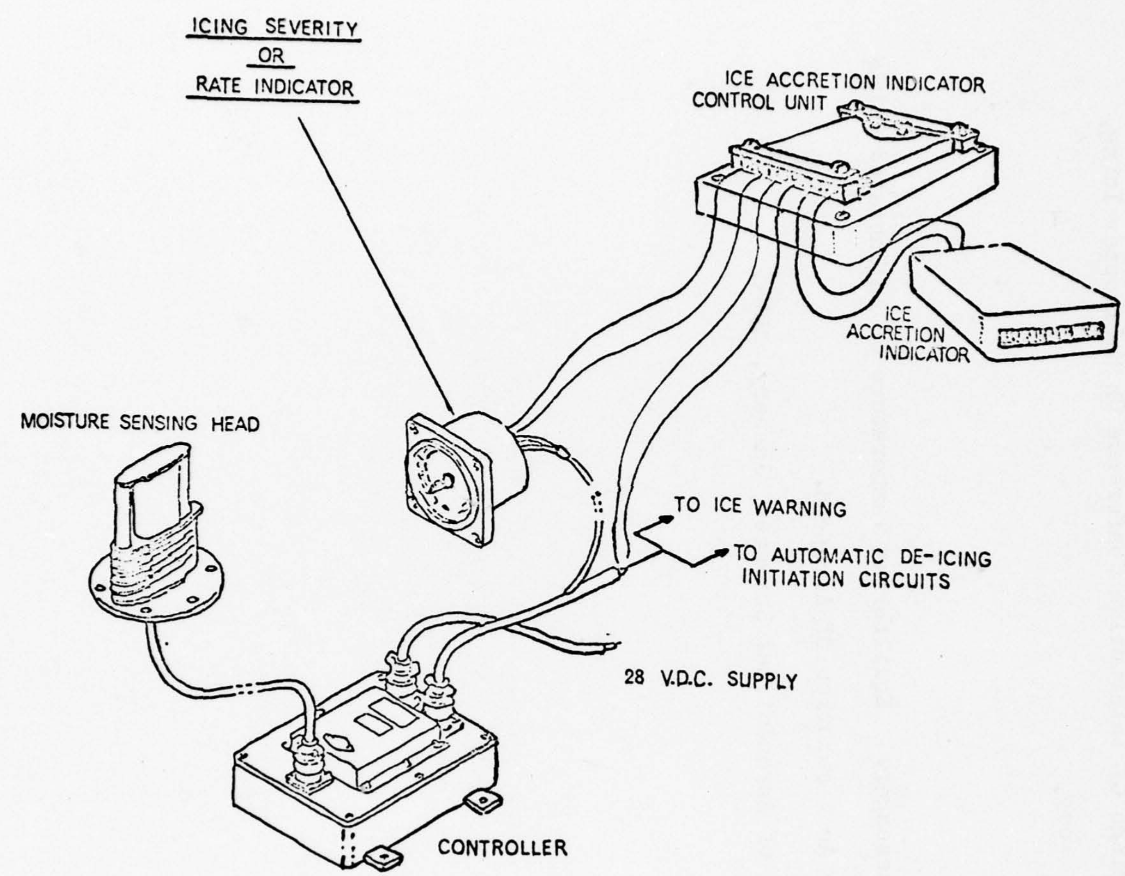


FIG. I INFERENTIAL ICE DETECTOR SYSTEM COMPONENTS

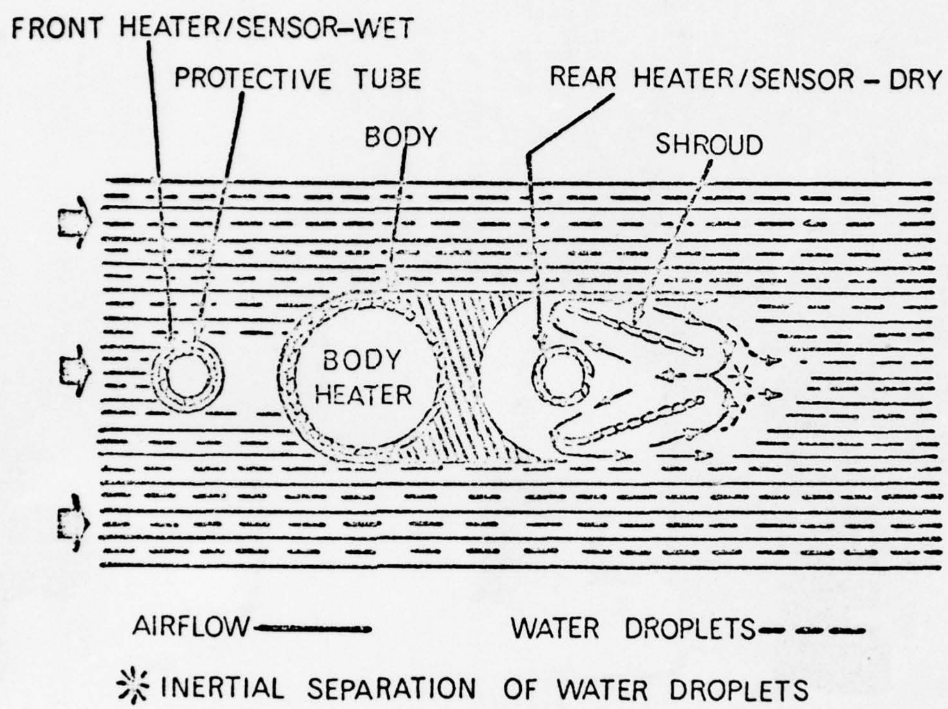


FIG. 2 SECTIONAL VIEW OF INFERENTIAL ICE DETECTOR

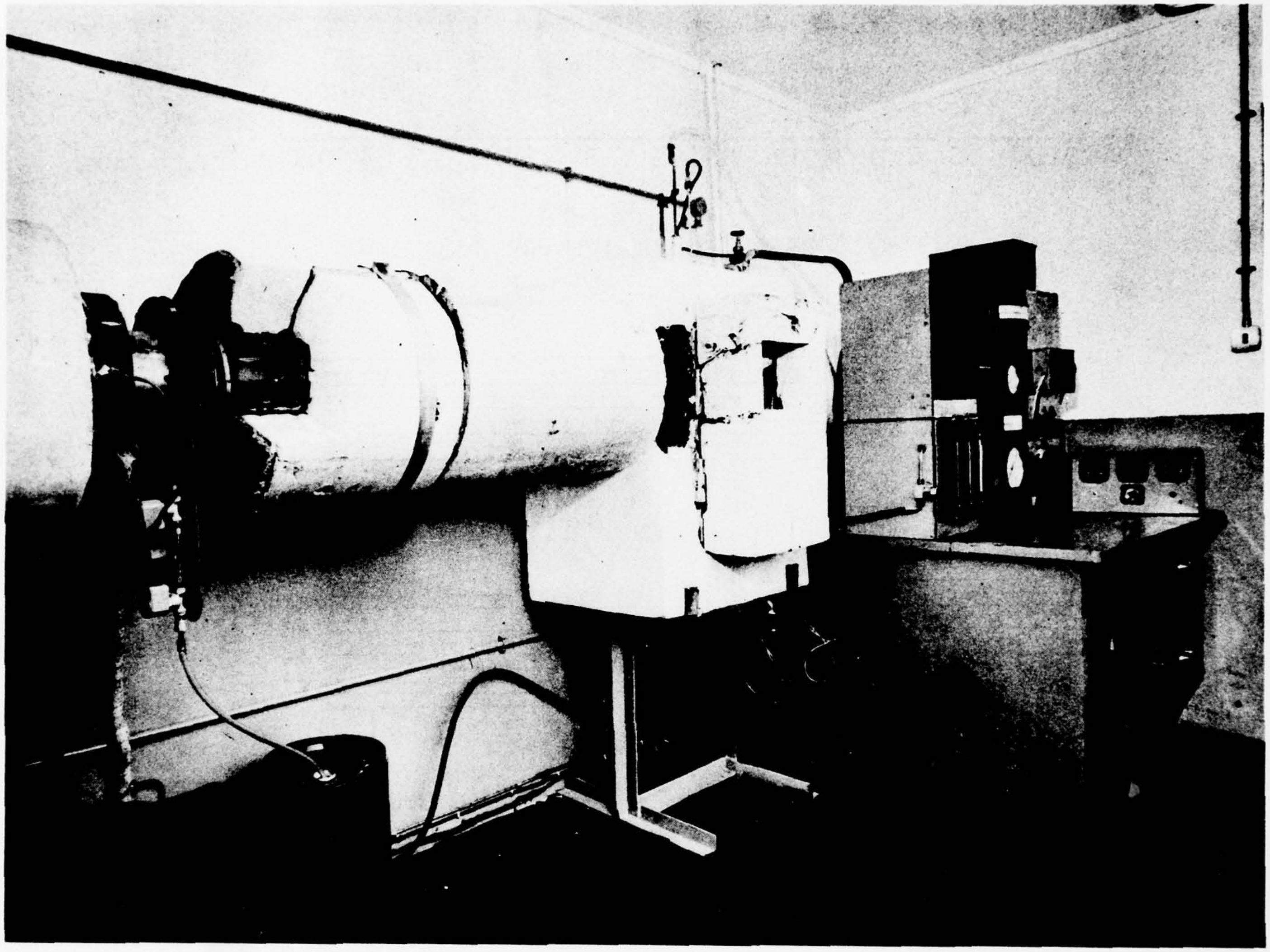


FIG.3 - ICING WIND TUNNEL TEST FACILITY

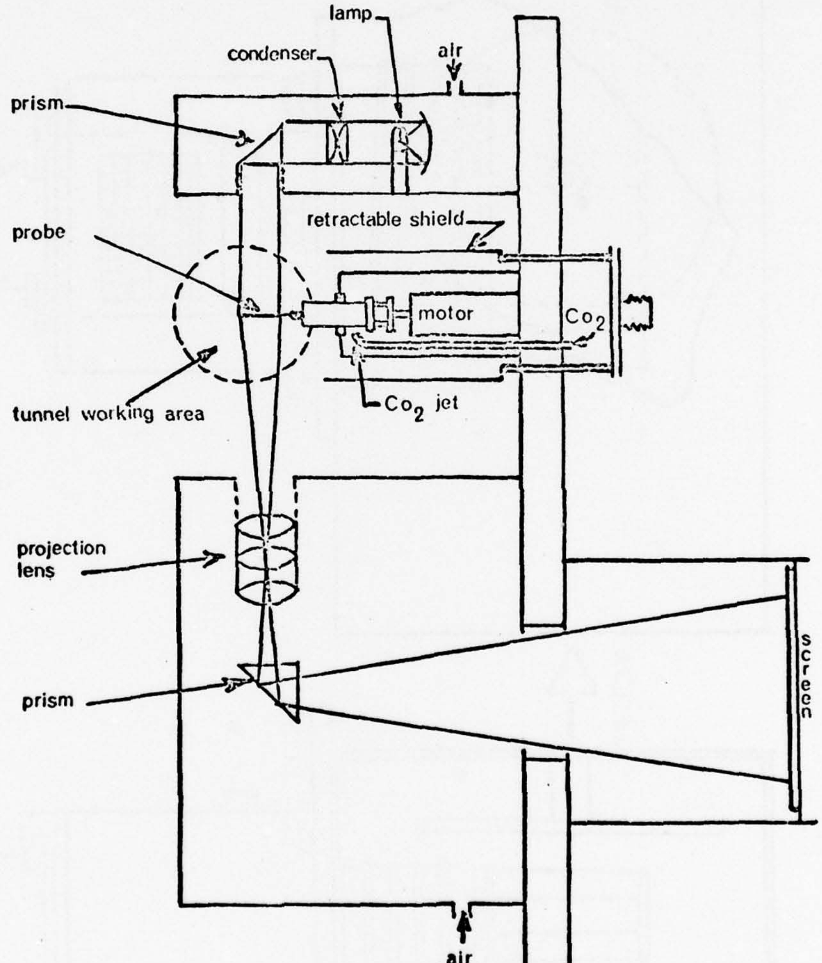


FIG. 4

CROSS SECTION OF T.A.C. ICING TUNNEL WATER CONCENTRATION CALIBRATION RIG

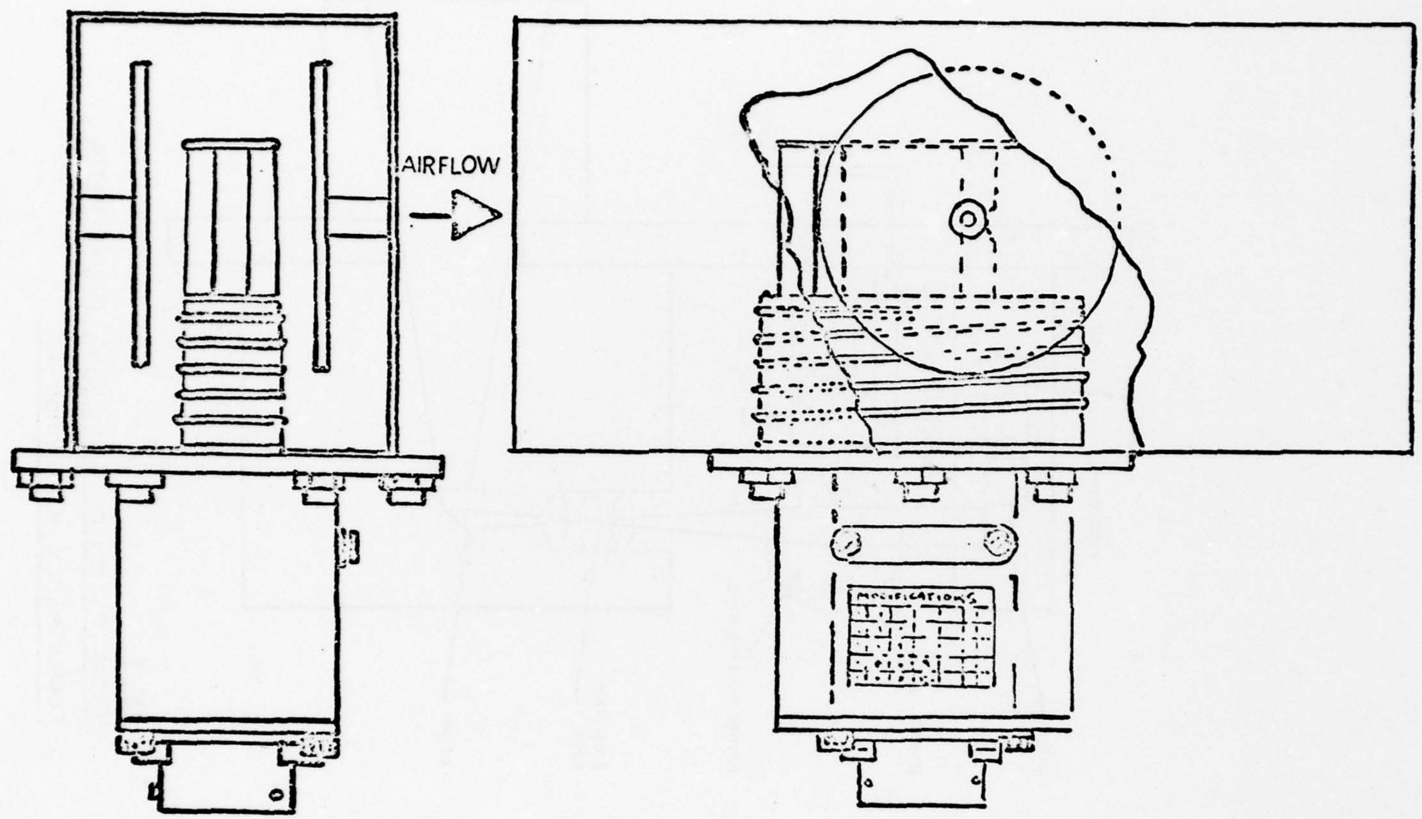


FIG. 5

Moisture sensing head, mounted in airflow straightener assembly.

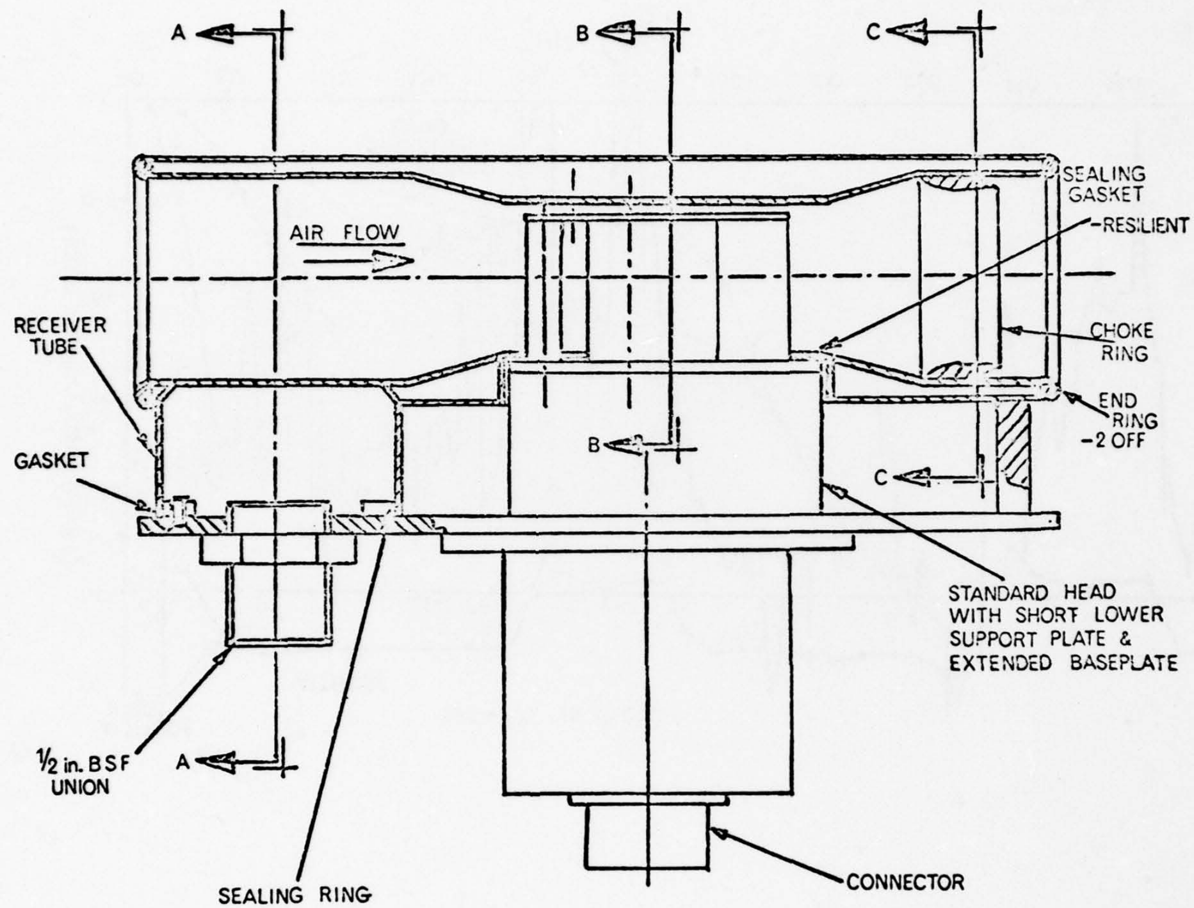


FIG. 6 SECTIONAL VIEW OF ICE DETECTOR AIRFLOW INDUCER

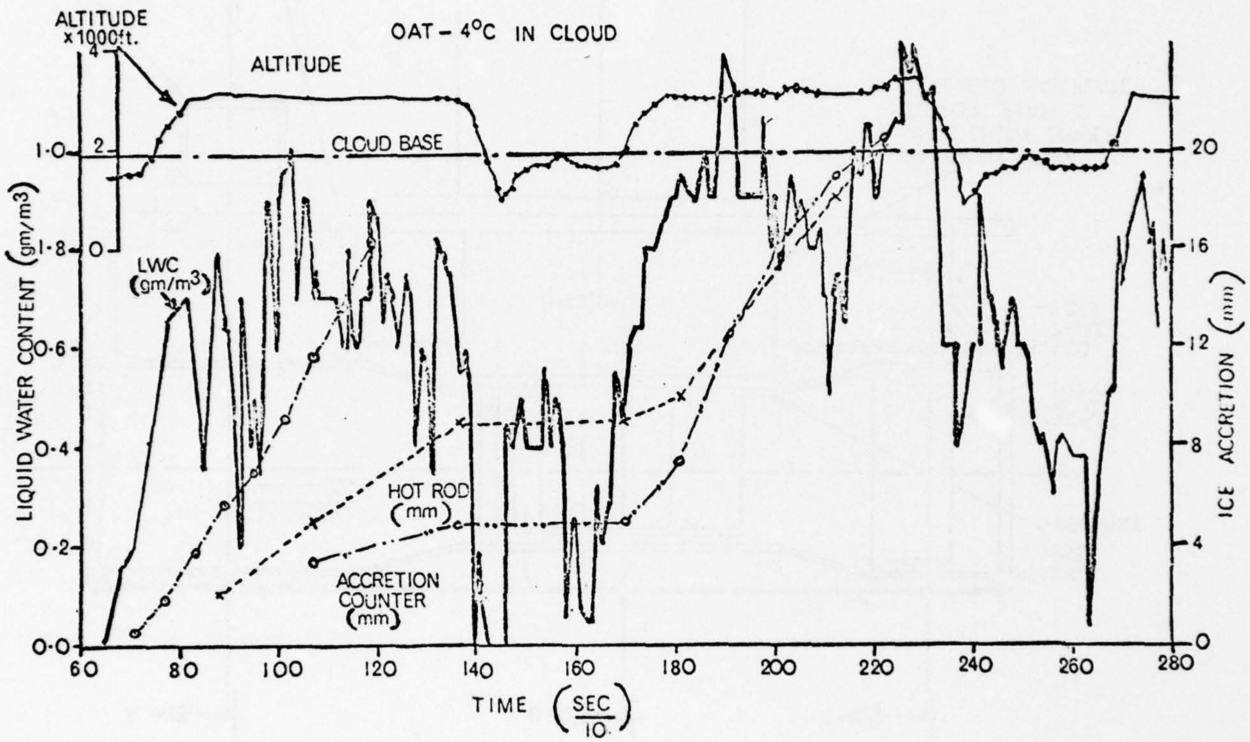


FIG. 7 TYPICAL ICING TRIAL RESULT. WESSEX 5

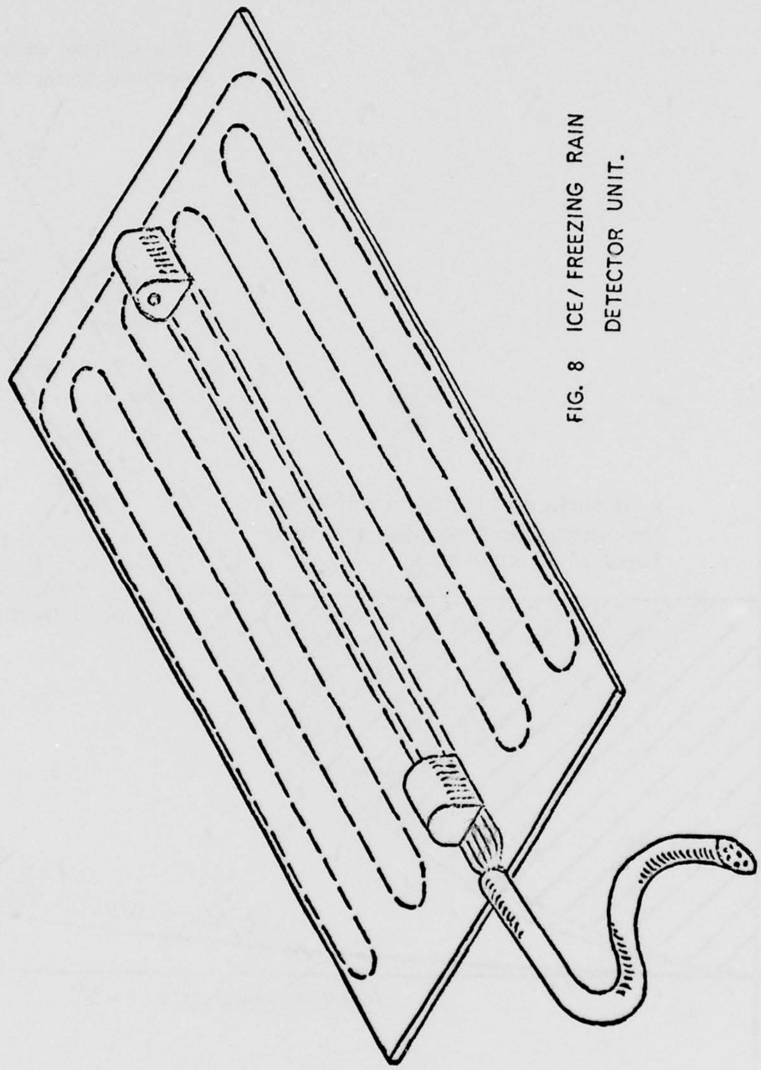
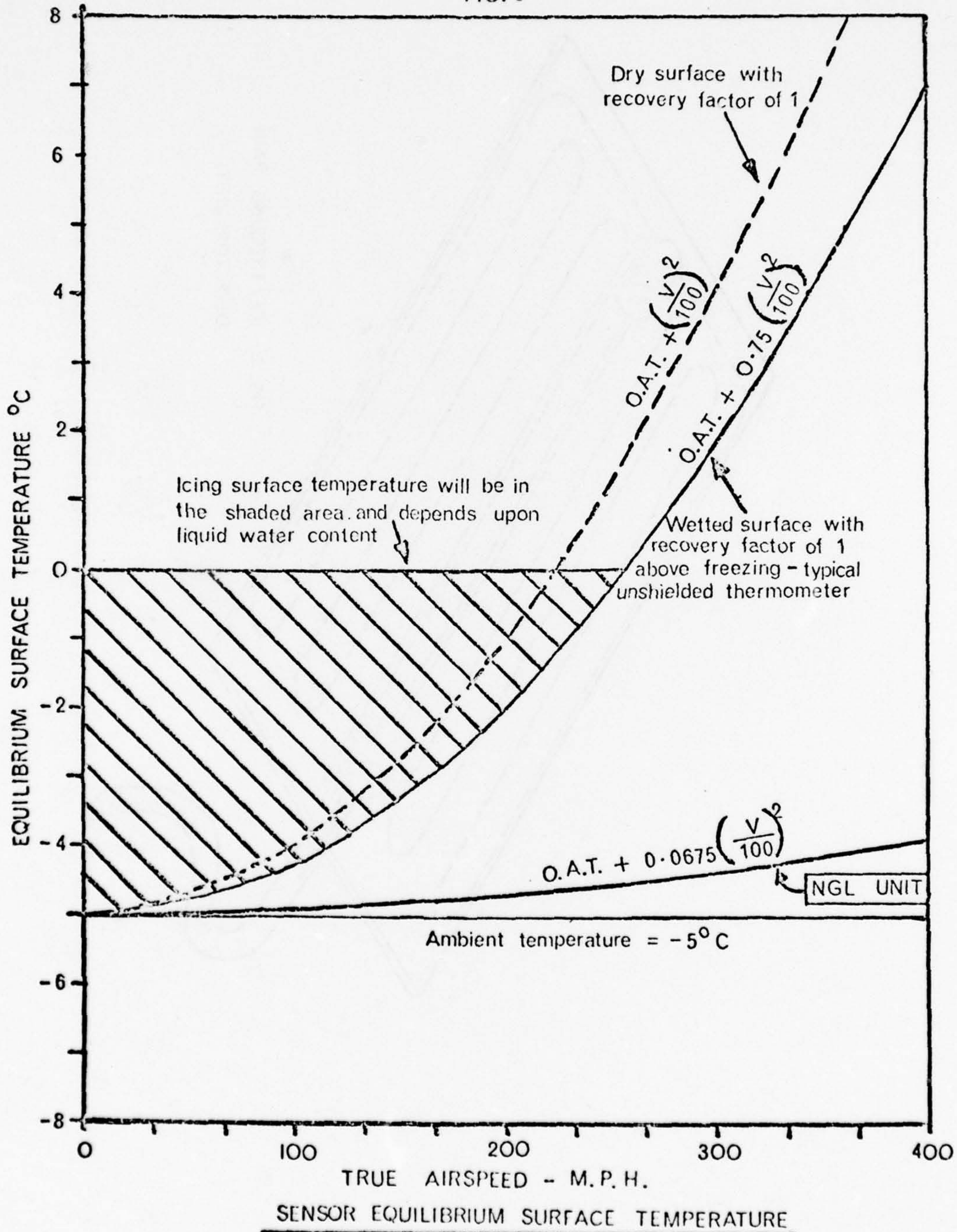


FIG. 8 ICE/ FREEZING RAIN DETECTOR UNIT.

FIG. 9



SENSOR EQUILIBRIUM SURFACE TEMPERATURE

TEMPERATURE SENSOR

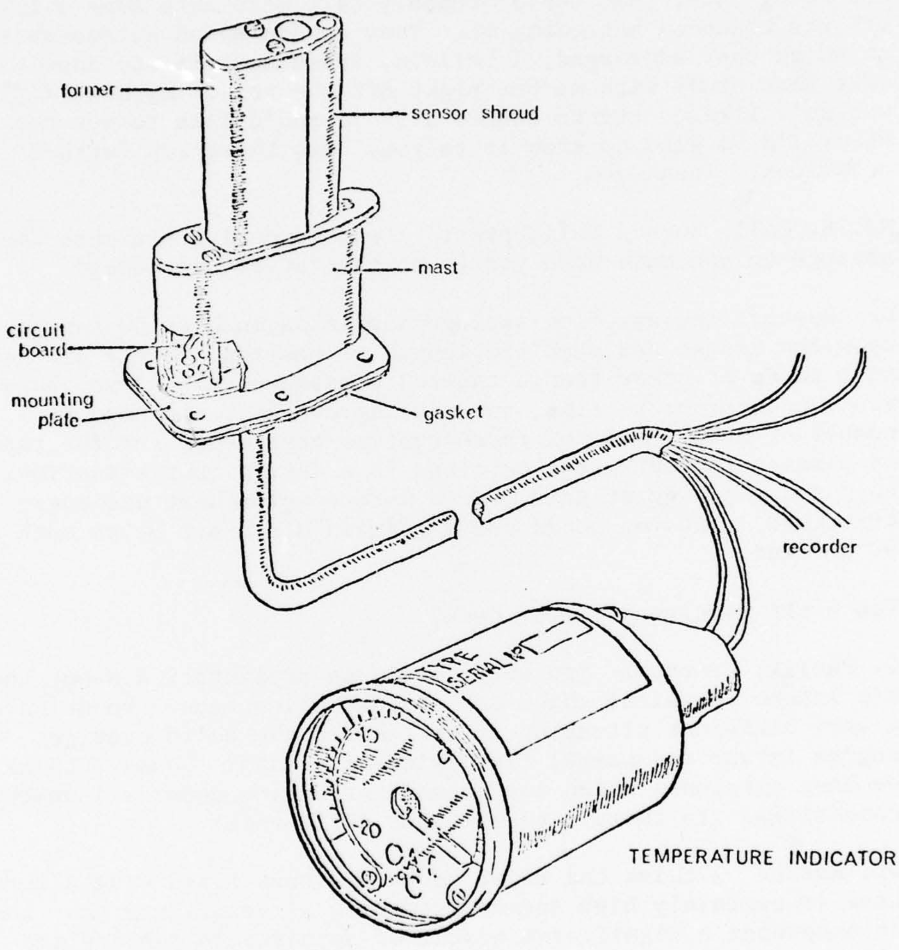


FIG. 10 O.A.T. INDICATOR SYSTEM COMPONENTS.

SESSION II DISCUSSION

CPT Checketts, London: What's the U.S. Army's view on the need for flight in snow, recirculating snow, clear of clouds? Do you see this as any additional limitations on your capabilities?

CPT Pike: Sir, this would probably fall more into line with the efforts Lockheed has going on. They conducted an extensive study in which they addressed, I believe, freezing rain and snow. I have that study with me but right off the top of my head I wouldn't like to try to answer it. If you'd like to see the study I'd be glad to show it to you. Are there any further questions? Thank you.

Mr. B. Hall, Hughes Helicopter: I was wondering how much air flow savings do you have when you go to the tapered passages?

Dr. Rosen: The air flow savings can be as much as 50 percent. Depends upon the design and specific length of passage. There are other ways to do it other than a tapered passage as all of you know, you can incorporate fins, you can improve heat exchange by a number of means. All of these systems cost money and the tapered passage concept gets you close to a design cost situation. It buys you the biggest gain over a more complex heat exchanger structure. But you could see a gain in bleed air by as much as 50 percent.

Yes - the gentleman in the back.

G. Paclik, Garrett: You were giving us presentation about the air intake, physical shape and so for helicopters. Do we have a very different situation if we compare the helicopter jet engine intake and normal fixed wing airplanes? Cause I think we have airplanes which are capable of flying under all weather conditions. Is there a significant difference?

Dr. Rosen: I think the major advantage that fixed wing aircraft have is certainly high speed fixed wing aircraft, are that they do encounter a significant amount of aerodynamic heating and this could be very significant. The V^2 term does get to be quite significant. The inlet however on a helicopter is such that it has to be designed and take into account all the peripheral areas surrounding it. There's usually a lot more junk on a helicopter, pylons and things of this sort which are setting out either adjacent to or nearby the helicopter. A low speed aircraft, of course, fixed wing aircraft, would definitely have to have its engine air inlet heated and in fact most jet fighters, of course, do have their engine air inlets heated. The major difference I think between a helicopter system and a fixed wing system has to be considered to be the rotor blade and the

characteristics of that rotor blade, and how that rotor blade operates in icing conditions.

Yes?

Mr. Friedlander, French Test Center: I think that the big difference between helicopters and aircraft is in the position of the engine. If you can position the engine of your helicopters as the same position of the fixed wing aircraft is clear from ice coming from the front part you have no problems.

Dr. Rosen: That is quite correct sir, however, many of us who have had to package designs within the C-130 (air transportability) and face up to those problems have not been able to have that latitude. I can tell you this that it's a tough decision to make. Its a tough decision whether or not you put a shield up in front of that thing or whether or not you add an additional drive shaft, whether or not you add an accessory gear box. It's a decision that has to be made not in light of icing alone but consistent with the whole design to cost and meeting the requirements philosophy that we are all faced with today. But your statement by itself is a correct statement.

SQDN LDR Lake: There are 3 points I would like to make. First, my reservations about pneumatic systems is that while you test them beautifully at 110 knots at heavy weight you never seem to look after me when I want to get down in a hurry and on a very low engine power and this is just the time I don't want to be concerned that my engine might go out. The question I would like to ask you is one near and dear to our hearts and that is the mixed condition of snow and ice and I was hoping Patuxent River was going to talk about this, but they obviously are not going to get to their feet. Our experience is that once you get ice if you then encounter snow you can't recognize it if you are flying instruments. How are you going to cope with that with your filteration systems particularly. The 3rd point that I would disagree with you absolutely fundamentally and I think this is something that the Colonel should take up in his forceful manner. I disagree absolutely that we can compromise the design for other design criteria. The fact that we've been at this game for 15 years and have made very little progress, I would attribute mainly to the fact that the designer hasn't started with icing in mind in the very beginning of the program and has compromised the icing design and ability the moment he puts his felt tip pen onto his paper or these days if he puts his flashy pen onto his cathode ray tube.

Dr. Rosen: I'm going to be very direct in my answer because I disagree with you. For one thing, it's one thing to do something and not know what your doing. And I say this with no arrogance, but when you make a decision as to where an inlet is going to be positioned today, it's not 1950, you know what your doing, you know darn well what your doing, you know darn well what the potential is of having a slug of ice come back at you and you've thought out in advance just what options are open to you. I don't want you to be misled by my statement. But I want to tell you this, that when your setting with a design to cost goal and you've got so many dollars to play with and you've got to meet that goal, well your jolly well going to meet that goal and you're going to do it and your going to meet the icing requirement as well. Your not going to forget about it. No way are you going to forget about it, but you've got to meet all of them and that's what makes the great challenge. And just by positioning the engine inlet you just don't position an engine inlet, you may end up positioning an entire propulsion package which could result in an increase, a very significant increase in cost and a very significant increase in weight. And there may be other ways to solve the problem, in fact there are, and in fact we have addressed ourselves to exactly that point. The other question on bleed air. Bleed air designers don't just arbitrarily pick design points. What they do is, they scan and I should have gotten into this. They do, they scan all of the characteristic speeds in which the aircraft is going to operate. This goes all the way from hover up to the max speed of the aircraft and at the same time scan the minimum possible engine power condition that you could be operating at, and still enter an icing condition. In this way, you design not for max power, no way, you design for minimum power; and this way try to come up with a low power, worst possible combination that is, the combination that produces the worst conditions on external aerodynamics and external thermal dynamics to produce an icing condition; and the similar condition of low engine power which would produce the lowest bleed pressure and lowest air temperature to combat that icing condition. So, you don't arbitrarily select one bleed point. This is not unique of Sikorsky, but all of us in this business certainly can address ourselves to the design requirements across the board.

Now the other question. Ron Price cracked up when you asked that question. Now it's a difficult problem, it's almost an impossible problem. It's not an impossible problem, it's one we just don't know how to solve right now. No one does. The watt densities involved are enormous, the amount of heat flux that you have to apply is absolutely horrendous. Those of us

who've calculated generator power to combat a freezing rain condition have just stood back in awe. Now that doesn't mean it can't be solved, I'm simply indicating that it has not been solved to date. It's something we must solve, it's something we haven't solved. I know you as aviators don't give a damn but I've simply got to tell it the way it is.

Mr. R. Gaertner, NASC: I'd like to say we don't really put icing last, in fact in the new specifications you'll find it's called out in some detail. We also have to worry about the engine installation; where it's going to go for effects of sand, dust, and maintenance and all these other things. It is a compromise, and you can't just look at icing all by itself. We are attempting to cover all these areas and give everyone a fair chance. And as far as the fixed wing goes, we have no Navy fighters that are anti-iced fixed wing; and we've never really had any difficulty with them either.

Our problem is mostly rain; and that's when its just so much rain it actually puts out the fire. But our icing, we normally fly above it or if we have to go thru it, we penetrate it fairly rapidly. So, we have not had the problem. I think you made the statement that there might be some anti-icing capabilities in fixed wing aircraft. In the Navy there isn't, there may be in the Air Force, there may be in the Army.

Dr. Rosen: There certainly are in commercial. We have anti-icing on the engine and we have ice detectors; but we do not anti-ice the inlets. There's no way we could do it. The inlets are too big, too long. You've got a 20-foot inlet, you just couldn't do it.

Well the JT9D for instance is pretty big and its got some heat. The JT3D is pretty big, not quite as big.

Mr. Gaertner: Your using mostly bell mouths too, you see, we're designing for speeds somewhat higher and we don't use bell mouths and its a little different.

Are there any other comments?

Lieutenant Commander Dayton, Coast Guard: I've got to ask the question, I can't wait any longer. About twice here you've mentioned rotor blades but you did it very briefly. I realize this is probably not your primary field but do you have any stand on your company's position or feel for what they're doing in that field?

Dr. Rosen: Sikorsky has, and I mean this is a difficult question. So I'll answer it. Sikorsky has an ongoing R&D program specifically tailored to that problem. We are spending our own funds. We are working on the problem. We have come up with preliminary designs and are at the point of going further. There is no question about it, we face up to it and we are ready to move ahead on it. Our position is that we've got to continue funding this program and we've got to continue the R&D effort that we have begun.

J. Cox, Cox and Company: Do you have anti-ice rotor blades on a Canadian customer?

Yes we do on the HSS2.

It's a 4 zone system roughly running at about 25 watts per square inch. It has a controller; basically it is a deice system. We allow ice to accrete on the surface of the rotor blade in a zonal pattern. The ice accretes, we apply power periodically. The inertial forces act on the ice and carry the pieces away in a controlled manner. The system has worked, it has worked with a certain amount of success and I feel that technology of course is available to us and is available to many of you who are aware of it. I don't know what else I can say, John, except that we do have a system and it has worked.

Mr. Wilson: (Responding to a question asked of Mr. Sewell) Well, I didn't come prepared with any figures to talk on this particular subject but suffice to say; having got interested in John's work, we managed to organize a couple of blades on the first season of testing which we tested in the rig on a Wessex and subsequently tested in natural icing. A lot of what he has said appeared to be borne out in that we were getting better fragmentation. There was evidence of marked reduction in adhesion and not the same tendency to leave remnants of ice on the rotor blade, which is something I shall be touching on on Thursday morning. On the second season, we managed to get another couple of blades and make up the set, and in fact went for a more sophisticated scheme, such as is shown on the slide where we got a composite covering to overcome what was thought to be some of the problems areas. Mainly in a neoprene leading edge strip in the maximum impact area to reduce the effect of rain erosion. That is spot on the leading edge and tapering of the sub strate to fair in better to the rotor blade contour. This we flew again, did further rig work, and followed by flights in natural icing; but I'm afraid because of priorities, which incidentally were outside of my control, we had to stop this

work at that point in the season. But I think it is certainly showing sufficient promise to carry on with full scale testing. This is one of the items on our program for next winter. I don't think there's a lot more to say really, other than we are taking a renewed interest in this field and after all, John talked about the reduction in the cohesive forces. I'd like to draw your attention to the fact that relatively recent studies on the porpoise have shown that in fact this is the reason why it has such a good hydrodynamic performance. Thank you.

Dr. Rosen: I think we ought to make one point, as our great leader says, perfectly clear. The modern rotor blade deicing system, and I use the word deicing system, does in fact utilize the energy of rotation and, in fact the basic principle does revolve around this point. When we do electrically heat rotor blades do not attempt to anti-ice the rotor blade. We attempt to deice the rotor blade and effectively break the bond and use the inertial forces which are there, which as you said are there, to carry away the piece of ice. Now the question is this, "How big is the piece of ice?" What I'm going to ask you now, you may or may not have an answer for, and that is in your studies have you been able to predict consistent with say typical helicopter rotor systems how large a piece of ice, in fact, will be shed? In other words, what inertial forces will be necessary to overcome the bond between the surface and the ice?

Mr. Sewell: Well, I don't think enough trials work has actually been done. As Alan mentioned we shall be doing more, but from laboratory experiments the lower the adhesion of ice, the smaller the particles. If your adhesion is comparatively good you have to generally build up a thicker layer of ice before it will crack off. Because you want the centrifigual forces on it and so it does depend on how good a crack propagator you have and it will depend on the thickness of the sponge rubber as well as how much flexibility you can tolerate.

Dr. Rosen: I think all of us understand the concept. What I'm getting at is the specifics. If you were to tell us that the piece of ice, the strip of ice, would have to be in the order 3/4 of an inch thick in order to break the bond, many of us would become concerned. If your saying that the piece, the strip of ice, need be only 1/8 of an inch thick, well then perhaps we're not quite as concerned. So what I was concerned about here, is have you made an estimate, or are you prepared to offer a guess?

Mr. Sewell: Well, as I said I don't think we can estimate yet until we've done more trials because the scheme that we are trying is not necessarily the optimum. We are trying one material as an outer skin with one sponge rubber sub-strate. We could vary that, and as I say, we don't know in practice what the thickness would have to be. We've no idea of measuring this in laboratory measurements. I don't think we can do scale tests. I think we've got to do the full scale measurements to see. But as I said before the polyurethane is not the best material from the point of view of ice shedding. Ice has a higher adhesion to it than as polythane, PTFE or even some metals. Ideally one wouldn't choose it; but we've chosen it in the first instance to see whether we get a bonus and whether it is good enough and whether it's worth going further ahead. Can I just briefly say that we tried on the rocket launcher, which I described to use caps in the same sort of way that you've done. We tried various designs but the problem there was that when we got a complete covering of ice over the rocket face; the resistance to the rocket movement was such that if a rocket did come out, or could penetrate, it brought all the caps out at once, and in fact, we got sort of a lump of ice plus caps coming away. Also, it presented severe resistance to the rockets. We are bothered about the damage to the frangible nose caps, anyway. So we discarded that idea pretty quickly.

LTC Graham: We have not conducted that test to prove it to ourselves. There's one significant thing about a seminar like this is that unfortunately we do not have the people represented here that represent what we call the user. In other words, for the Army, the "TRADOC" type people. Because we can churn all we want about what the Army needs, but until those people that represent the user make their requirements known on what the capabilities of the system must have, there's no money.

THE AIMS OF THE UNITED KINGDOM'S HELICOPTER ICING PROGRAMME

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SUMMARY

A brief indication of the aims and achievements of the UK's helicopter icing programme is given. Definition of the icing environment and meteorological probabilities are outlined. Protection priorities are declared and the broad development state of each reviewed. Icing hazards and associated flight safety matters are stressed. The scope of icing simulation facilities is mentioned.

INTRODUCTION

I hope that what I am going to say during the next 15 minutes or so, as seen from my chair in the Helicopter Projects Directorate in the UK Ministry of Defence, will serve to set the scene for the more specialised presentations which follow from other members of our delegation. May I say first of all how pleased I am that the UK has been given the opportunity to contribute to this symposium.

The original specifications for the UK's current in-Service helicopters all recognised in varying degrees the requirement to operate in icing conditions. However, at the time these specifications were drawn up, the UK's defence policy placed rather more emphasis on operations in areas which have hot climates. Helicopters were accepted for use by the Services with releases which precluded flight in ambient icing conditions and with the minimum of testing, usually limited to a demonstration in a test tunnel that an uninstalled engine would continue to function in simulated icing conditions. Towards the end of the 1960's there was a shift in emphasis in UK's defence thinking away from tropical climates. Coincidentally there occurred an increasing requirement for tactical exploitation of the helicopter's relatively recently acquired all-weather-flight capability. These factors pointed up the need to give greater attention to performance in icing regimes.

There can be no doubt about UK's ultimate aim now - unrestricted flight in icing conditions. However, it must be said that in the past UK's efforts have centred on development rather than research, essentially using and adapting

techniques established for fixed wing aircraft, which of course have the great advantage that they can in many cases climb out of icing conditions. To date, we would not claim to have provided any particular helicopter type with adequate protection. The problems are numerous and lack precise definition. There are few worthwhile records (but many random and unquantified incidents). Testing is extremely difficult and expensive, and the icing season is short.

THE ICING ENVIRONMENT

Probably the most fundamental problem is that of defining the environment against which to protect the helicopter. We have much information about the upper atmosphere but relatively little about the height band in which helicopters operate.

The identification of clouds in which classical icing can occur is easy - we can measure liquid water content and temperature - but, as I have said, there is a dearth of data about the lower atmosphere with which we are concerned and, as is well known, no cloud is homogeneous, let alone repeatable. Recent years' trials show that pockets of high LWC concentration can be encountered in stratus clouds: this suggests that for protective equipment design purposes, it may be necessary to apply a short term exposure factor of 100% to the nominal value of continuous maximum LWC appropriate to a given temperature. Snow is not at this stage adequately defined and nor are mixed conditions or freezing rain. We make no attempt to provide airframe protection against the last mentioned.

The probability of encountering icing conditions is an important factor relevant to the cost effectiveness of protective hardware. UK has studied the probability of encountering freezing cloud up to 5,000 ft over Northern Europe and the Eastern Atlantic. Figures 1 and 2 show typical isopleths of percentage probability: they sensibly agree with USAF Air Weather Service Report 220 dated June 1972. Within such clouds the probability of actual encountering icing is 50% as a good round figure (Russian information says 20-80%). Whilst the possible existence of an icing condition can easily be forecast, its probable severity cannot: we do not at present visualize a research programme which might improve this situation. The occurrence of snow may add to any operational incapacity due to icing: its additional effects are most significant below the cloud base.

Almost three centuries worth of data on snow in the vicinity of UK is currently being analysed.

PROTECTION PRIORITIES

In the course of our studies in the UK, we have decided upon the following priorities:

1 Full engine and air intake protection in all weather conditions.

2 Clear view through forward windscreens.

3 Ice accretion and icing severity indication.

4 Rotor blade protection.

The problem of engine and air intake protection is largely overcome at the initial design stage by the very siting of the engine. We have in hand a programme of research to investigate potentialities of a number of different intake configurations. Here it is pertinent to note that in any scale model testing of intakes the water droplets must also be scaled to ensure representative distribution from momentum considerations. We have found that single engines mounted behind transmission gear boxes appear to derive a protection bonus, eg Wasp and Gazelle. Grids are attractive for protection against shed ice but they could produce more problems than they cure: we are exploring the possibilities of anti iced grids.

Visibility through forward windscreens can be ensured for modest electrical power outlay using metallic oxide films.

In the area of ice accretion and severity indication, we have a long way to go. Although in practice indication of ice accretion can be achieved by a small aerofoil section some 6" long sited within the pilot's field of view, as a breed icing severity indicators do not work. A difficult compromise is invited between the requirements of forward flight and the hover. Attempts to overcome this by induced flow over sensors have not been very successful.

Hitherto we have depended upon natural shedding of ice from rotors and the need for rotor blade protection has been associated primarily with lower temperatures below approximately - 10°C. However, it is becoming increasingly

evident that such protection is required for protracted exposure to <u>any</u> icing condition in order to contain torque increases and to conserve an autorotative capability adequate to make a survivable engine-off landing.

Additionally, accurate indication of outside air temperature becomes of vital importance when critical restrictions are imposed, particularly at or just above freezing point.

As far as rotor blade protection is concerned, the UK as so far only embarked upon the development of a heated rotor blade system employing orthodox leading edge electro-thermal de-icing mats, triggered in a cyclic fashion by a UCC ice detector. However, limited trials have demonstrated that its ability to cope reliably with the higher liquid water concentrations now known to exist is suspect. Furthermore, there are also the obvious disadvantages of complication, weight and power requirements inherent in such a system. A better solution may be to <u>anti</u>-ice the rotor, perhaps using a podded APU, on a role/climatic basis.

In passing I might mention that the UK has not encountered any problems due to ice accretion on tail rotors.

We have some evidence that leading edge coatings such as polyurethane and nylon improve the self shedding of ice from rotors, particularly when used over a flexible substrate. We are attracted by the relative simplicity of such protective methods and plan further trials to evaluate them.

FLIGHT TESTING AND RELEASES

The difficulties of icing flight testing are well known - the short season, high cost, difficulties of adequate observation and measurement. Acknowledging the risks, UK sets very strict flight safety criteria for the conduct of trials. Comparable criteria cannot sensibly be applied in releases for Service users if they are to be operationally worthwhile: in giving any release for flight in icing conditions the user is inevitably placed in an abnormally high potential risk situation. This factor places a heavy responsibility on those responsible for authorising flights in possible and actual icing conditions, and requires a deep and detailed knowledge of the hazards and the limitations of the aircraft.

It is worth noting the potential operational benefits of separate releases for flight in snow (clear of cloud) and in

cloud icing. Whilst it may be difficult to clear some aircraft for both conditions, (but practically impossible and certainly unwise to clear any mixture of the two), either may be achievable in isolation with comparative ease.

SIMULATION FACILITIES

The UK makes the maxium possible use of simulation facilities: our two largest are the Aeroplane and Armament Experimental Establishment's open jet tunnel having a maximum 8 ft diameter jet and employing liquid nitrogen as the cooling medium, and the large altitude engine test cell at the National Gas Turbine Establishment, Pyestock. In the open jet tunnel intake testing at representative forward speeds can be undertaken with locked power turbines or with rotors running clear of the airstream, according to helicopter size/configuration. In an endeavour to extend its use to the investigation of rotor blade icing we shall shortly examine, using a semi-rigid rotor, the effects of rotating blades intersecting the tunnel airstream.

Full scale fuselage testing, with engines running or with simulated air flows and heat emissions, can be undertaken at the National Gas Turbine Establishment. One problem we have yet to solve is that of producing artificial snow; then we need to tackle simulation of mixed conditions.

We believe that simulation facilities such as these provide quick and economic pointers to problem areas and are most useful development tools. As a logical extension we consider that the US Army's CH 47 icing tanker has enormous potential: also we look forward to the possibility, albeit only faint at present, of one day sharing a European icing rig similar to the Canadian National Research Council's installation at Ottawa. In all such facilities meticulous equipment calibration and icing cloud measurement is, of course, of paramount importance.

HAZARDS

Operators, be they Service or Civil, have a healthy respect for the hazards of icing conditions, but at present, due to the lack of protective hardware, the vast majority are inexperienced and are in general advised to keep clear. Thus there is a need for pilot education which should not overlook some of the less obvious points which might catch people out. To mention a few:

1 Level and rate of torque rise

Four considerations:

i Imperative that this remains below the fatigue damaging threshold.

ii Ability to maintain height, even at reduced speed.

iii The need to maintain autorotative capability.

iv Last, but not least, the need to maintain an escape route - be it up, down or back. Flight planning and authorisation are thus very important.

2 The dangers of ingestion of shed ice during flight, landing and ground taxying above $0^{\circ}C$, following exposure to icing conditions.

3 FOD due to ingestion of fragmented ice or compacted snow, from the ground or deck of a ship, especially when operating in close company with other helicopters.

4 The need to remove fallen snow from warm rotor blades prior to start to avoid melt which can subsequently freeze.

(The unpopular alternative is to cool the aircraft to ambient temperature before exposing it to the elements). Nor must engine intakes be overlooked: it has happened!

5 Landing in deep powdered snow can produce a flame-out hazard, either due to direct ingestion or during heavy recirculation, but may not cause engine damage.

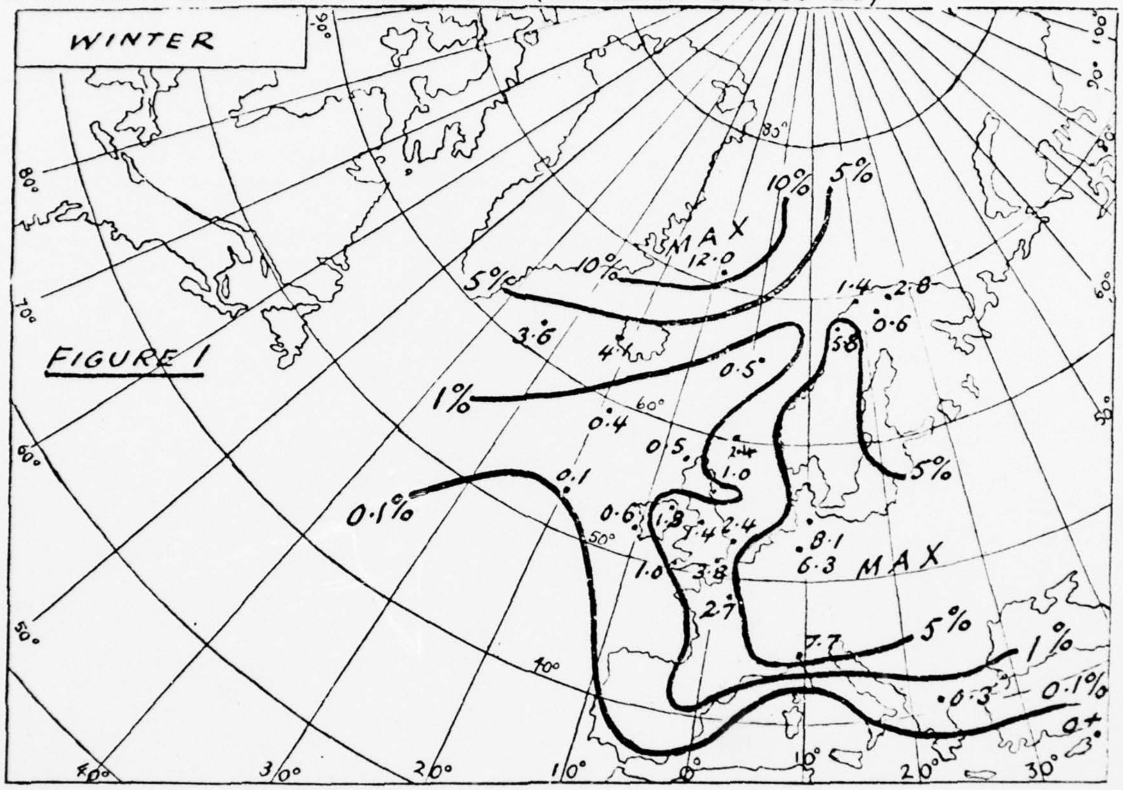
SUMMARY

Very sketchily I have outlined the UK's aims and achievements and a few of the lessons learned. In sum, icing is a hazardous environment. We do not know enough of its composition to define proper design criteria, nor can we yet provide the pilot with adequate warning indicators and full protection equipment. We are convinced that full engine protection is vital and now more and more recognise the need for rotor protection. We believe in maximum use of simulated test facilities. We are very much aware of the need for

caution in flight trials and in any possible release to operating authorities. There remains a great deal to learn and much to be done, which will inevitably be expensive in both time and money.

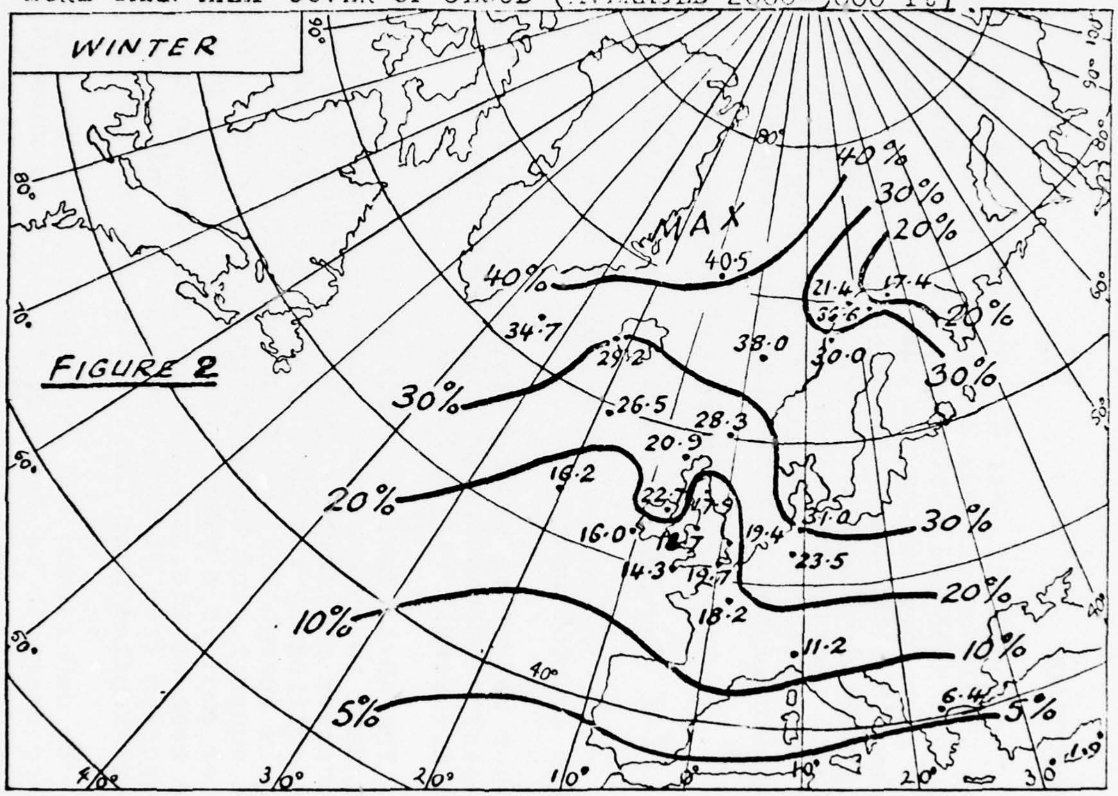
PROBABILITY OF FREEZING CLOUD

PERCENTAGE PROBABILITY OF TEMPERATURE $\leq 0^{o}C$ COMBINED WITH MORE THAN HALF COVER OF CLOUD (AVERAGED 0-1000 ft)



PROBABILITY OF FREEZING CLOUD

PERCENTAGE PROBABILITY OF TEMPERATURE $\leq 0^{\circ}C$ COMBINED WITH MORE THAN HALF COVER OF CLOUD (AVERAGED 2000-5000 ft)



RESULTS OF AH-1J ICING TESTS CONDUCTED JANUARY-FEBRUARY 1974

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INTRODUCTION

The Naval Air Test Center (NATC) has conducted icing trials on various series of the H-1, H-2, H-3, H-46, and H-53 helicopters in the U. S. Navy/Marine Corps inventory during the past fourteen years. In October 1973 the Naval Air Systems Command, Washington, D.C., tasked NATC to evaluate the capability of the AH-1J to operate in icing conditions. Specifically, NATC was tasked to evaluate AH-1J icing characteristics with emphasis on the following components:

1. The engine inlet and particle separator

2. The unheated 540 series main rotor system

3. The rain removal, pitot heat, and environmental control unit

Another objective of the evaluation was to obtain necessary information on icing operation for inclusion in the Aircraft Flight Manual.

The AH-1J Tactical Helicopter (Enclosure (1)) is a tandem, two-place, twin power section conventional helicopter utilizing a two-bladed rotor system designed specifically for the combat role. Its primary mission is search and target acquisition, multiple weapon fire support, and troop helicopter support. The helicopter employs a pitot heat system to keep the pitot tube free of ice, a rain removal system to keep the windscreen free of moisture and ice, and an environmental control unit for cockpit temperature control.

To understand the test results for the engine, it is necessary to be aware of the airflow through the inlet/engine. Enclosure (2) presents a propulsion system airflow diagram which shows the relative location of the inlet, engine, ejector, and the airflow path through the engine. Air enters the inlet and, just prior to the particle separator valve, can either

continue aft to exit the ejector or turn downstream to enter the engine inlet. Air entering the engine inlet screen passes through the engine and out the exhaust duct into the center of the ejector. The inlet/ejector act essentially as a nozzle while the high velocity exhaust duct gasses act as an ejector inducing a flow through the nozzle.

The ejector arrangement is the fundamental component of the particle separator system which is designed to separate 80% of all particles 20μ or larger and 93% of all particles 80μ or larger. Note that the particle separator screen and the engine inlet screen (Enclosure (3)), both of which are unheated, have a high potential as ice collectors.

TEST FACILITIES/CRITERIA

The U. S. Navy employed the unique National Research Council (NRC) of Canada Spray Rig as shown in Enclosure (4), for build-up tests prior to tests in natural icing conditions. The Spray Rig utilizes high pressure steam and water. The steam pressure forces the water through nozzles located on the metal grid work of the Rig. The Rig is used only when the air temperature is below freezing to ensure the atomized water droplets are supercooled after exiting the nozzles. The supercooled water droplets are then carried by ambient wind to the aircraft. Ice accretion rates encountered in forward flight are simulated in the Rig by varying the liquid water content (LWC) and micron size (μ) of the water droplets. For U.S. Navy testing purposes, the LWC was varied to simulate ice accretion rates at 150 kt and water droplet micron size was held constant at 30μ. Testing in the rig is limited by wind speed and ambient precipitation. A minimum wind speed of 5 kt is needed for tests. Precipitation degrades the LWC and increases the difficulty of quantifying the test data.

The tests were conducted under the following conditions:

1. Temperature range: $-4.0^{o}C$ to $-20.4^{o}C$

2. Icing cloud liquid water content: 0.32 gm/m^3 to 0.74 gm/m^3

3. Water droplet diameter: 30 Microns

4. Time in Spray Rig per flight: 5 to 60 minutes

5. Aircraft gross weight: 6,700 to 10,000 lb.

Of note are the temperature range and duration of tests in icing conditions. FAA and NASA weather data show evidence of icing conditions in temperatures as low as -35°C. However, the probability of encountering icing below -20°C and below 10,000 ft altitude (the upper limit of most helicopter operations) is extremely low. Therefore, for all U.S. Navy testing to date, -20°C has been used as a lower limit on icing tests.

For testing anti-ice or de-ice systems the criteria of ice-free operation over the entire temperature range for 30 minutes was employed. The AH-1J has an unheated engine inlet and rotor system, therefore a different time criteria was required. Sixty minutes was chosen as an optimum time period to allow an unheated system to accumulate sufficient ice to reach an end point.

The following parameters were recorded during the tests: Engine gas generator speed (N_g), engine inter-turbine temperature (ITT), transmission torque (Q), rotor speed (N_r), fuel quantity, and outside air temperature (OAT). These parameters were recorded every ten minutes while in icing conditions. The two heated systems (rain removal and pitot heat) were activated prior to entering icing conditions and deactivated as the aircraft departed the icing environment. Immediately after a test each system was inspected for ice accretion and photographed. The aircraft was completely cleared of ice prior to conducting the next test.

Safety criteria for test end points were as follows:

1. Ice accumulation on engine screens or inlet causing an ITT rise to maximum continuous power (767°C).

2. Sufficient ice accumulation on rotor system to produce either (a) an unacceptable airframe

vibration as determined qualitatively by pilot or (b) a 30% torque increase over that required to maintain the same hover altitude before ice accumulation.

3. The criteria for satisfactory rain removal and pitot heat operation was that the windshield and pitot tube remain free of ice over the temperature range of -20°C to 0°C.

The following FAA definitions were used in the icing tests:

1. Trace icing - 1/2 inch per 80 miles

2. Light icing - 1/2 inch per 40 miles

3. Moderate icing - 1/2 inch per 20 miles

4. Heavy icing - 1/2 inch per 10 miles or less

Note that time is not a factor in the definition.

RESULTS

Engines

Enclosures (5) through (8) illustrate engine inlet screen icing results at four representative temperatures. There were no differences between ice accumulations on the No. 1 and No. 2 engine compressor inlet screens. Ice covered the upper portion of the screens first, and progressed down the sides in the tests involving heavier icing conditions. The photograph in Enclosure (8) was taken following tests in the Spray Rig in moderate to heavy icing conditions (-20.4°C, 58 minutes). Two factors are of note: (1) ice never accumulated on the bottom one-third of the screen on any test conducted, and (2) after 60 minute runs in moderate to heavy icing conditions, no significant ITT rise due to airflow restriction to the engine was observed.

A typical view of the particle separator screen after a 60-minute test at -15.1°C is presented in Enclosure (9) and (10). Ice typically covered the screen and accreted into the airstream. At no time did the particle separator ice accumulations restrict the

airflow sufficiently to cause a significant reduction in engine performance or capability.

Two flights were flown in freezing rain at -5 and -2°C. Ice did not accumulate on the screens during either test. This was attributed to the increased particle separator efficiency in forward flight and to the large droplet size indicative of freezing rain.

Of the six flights in natural icing conditions, varying in intensity from trace to light icing at temperatures down to -10°C, the screens accumulated considerably less ice than under comparable conditions in the Spray Rig. The engine screens, inlets, and particle separators are considered satisfactory for flight in icing conditions.

Windshield, Pilot Heat, and Environmental Control Unit (ECU)

The pitot heat was satisfactory under all conditions tested. Correlation of pitot heat operation in the Spray Rig and natural icing conditions was excellent.

The rain removal system operates by blowing hot bleed air through small diameter tubes located at the base of the front windscreen to remove any moisture or ice. During all icing tests in the Spray Rig between 1/3 and 1/2 of the front windscreen was ice covered, limiting forward field of view. However, on all tests in natural icing the windscreen remained clear. This was due primarily to the reduced downwash effect and increased airstream mixing with the bleed air to provide a more efficient anti-ice capability and emphasized the need of employing natural icing tests to verify Spray Rig results.

The environmental control unit (ECU) provides temperature control for the cockpit and is regulated by a rheostat located in the pilot's cockpit. Outside air required for system operation is inducted through a screened intake located above the cockpit. The screened intake was obstructed by ice after 10 to 15 minutes in both simulated and natural icing conditions, as shown in Enclosure (11). A change in ECU turbine frequency was noted at approximately 30 to 35 minutes

indicating restriction of airflow. However, the ECU continued to operate satisfactorily for all tests. Continued operation in icing conditions could have a detrimental effect on system reliability. The icing problem might be eliminated by rerouting the ECU duct and screen to face into the transmission area.

540 Main Rotor System

Enclosures (12) through (15) demonstrate rotor system icing at four representative temperatures. The run at -16.5^{o}C for 60 minutes depicts the major deficiency with the AH-1J. The rotor system accreted ice, with an accompanying ITT and torque rise, for 20 to 25 minutes after entering icing conditions and then began to shed ice naturally. After 5 to 10 minutes the ice shedding cycle was complete and the ice began to rebuild. However, the shedding was asymmetrical on all icing flights resulting in unacceptable one-per-rev vibrations varying in intensity from light to severe.

Three techniques were investigated in an attempt to clear the rotor system after ice shedding commenced:

1. Collective pump - rapidly moving the collective pitch lever up and down for two to three cycles.

2. Rapid cyclic rotation - rapidly moving the cyclic stick in a 4 in. diameter circle through 720^{o}.

3. Rapid rotor RPM change - beeping the rotor RPM to minimum, then holding the beeper switch to increase to maximum to allow an RPM surge. RPM was then reset.

The collective pump had no effect when employed. The cyclic rotation technique was inconsistent in that the vibrations generally became more severe or didn't change, and only occasionally diminished. The rapid rotor RPM change was the most effective in lowering vibration levels after asymmetric shedding was encountered. The technique worked on every occasion and was successful in lowering vibration levels to normal after one cycle. However, only a limited evaluation was possible due to poor weather conditions.

Additional tests are needed to evaluate the full capabilities of this technique.

On one occasion, the tail rotor gearbox fairing was damaged by ice shed off the main rotor system on shutdown as shown in Enclosures (16) and (17). This was caused by a normal application of the rotor brake. A light application of the rotor brake on subsequent tests eliminated this problem and no further occurences were noted.

CONCLUSIONS

1. The AH-1J showed an excellent capability for flight through icing conditions and has the potential of becoming a true all-weather aircraft. However, the AH-1J can not be cleared for flight through natural icing conditions until correction of main rotor blade asymmetric ice shedding is accomplished.

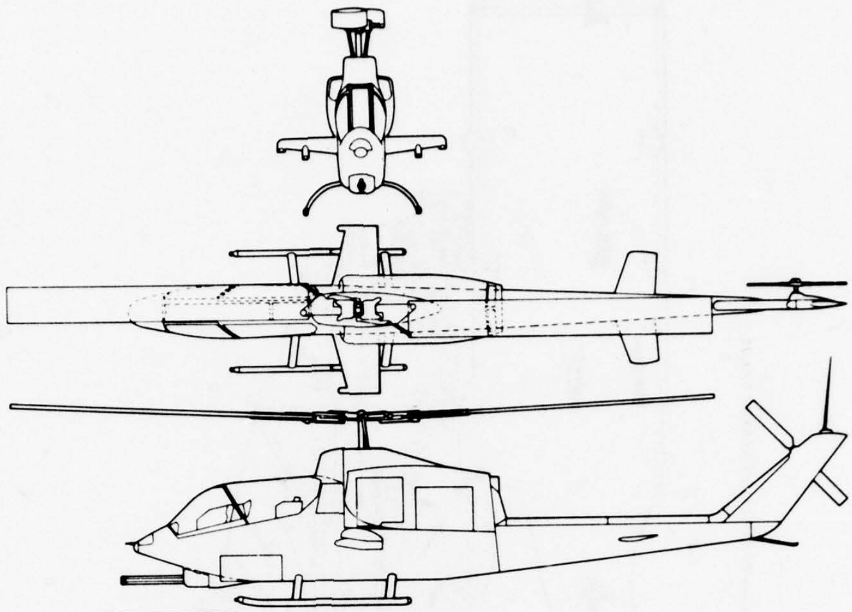
2. The engine inlet/intake and particle separator systems of the AH-1J helicopter are satisfactory for operation in icing conditions.

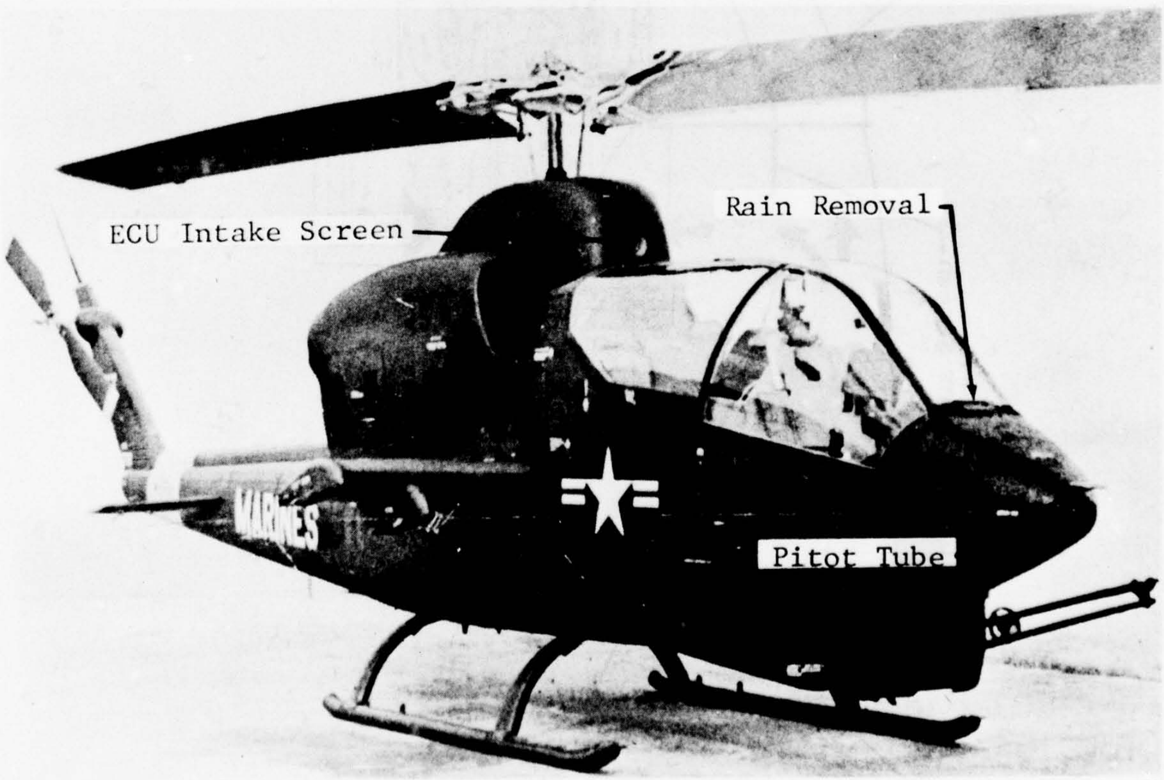
3. The rain removal and pitot heat systems are satisfactory for operation in light icing conditions.

NATC is presently pursuing tasks to conduct additional testing to expand the icing envelope of the aircraft and extensively explore the related problems.

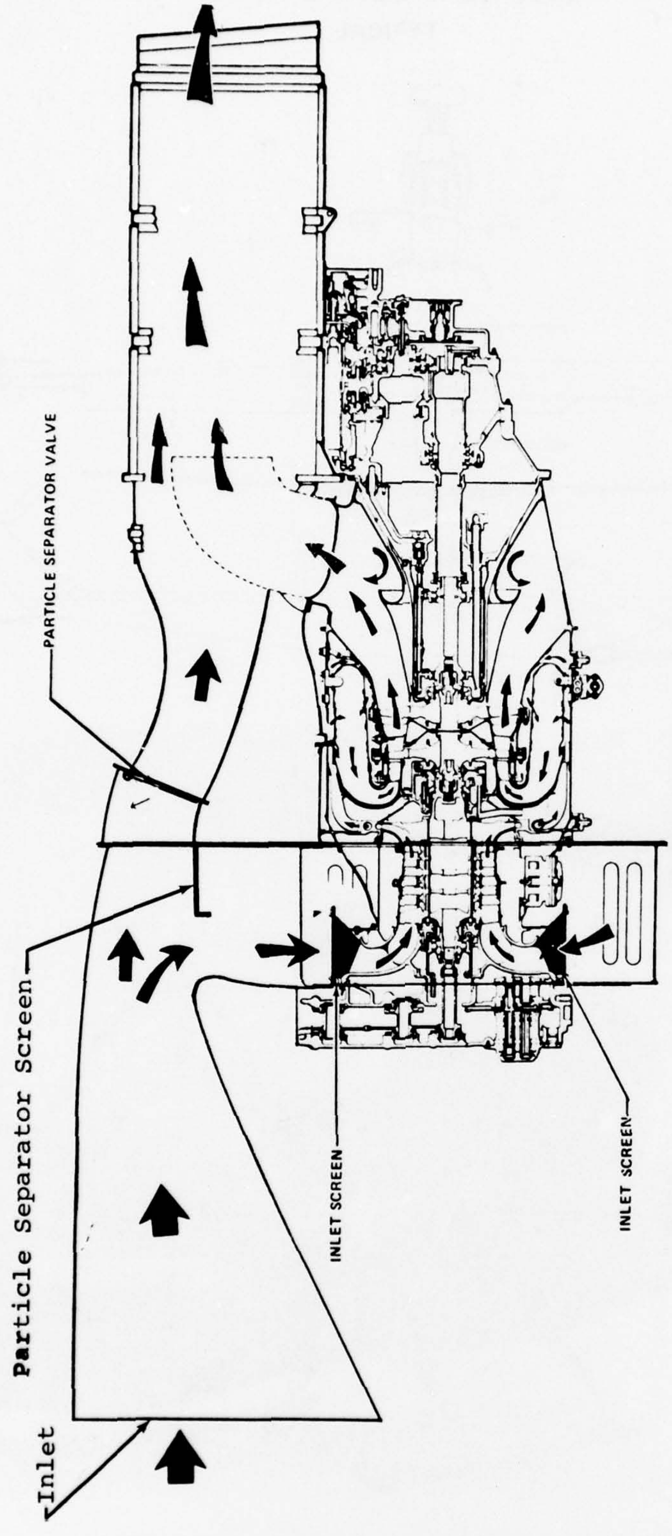
AH-1J HELICOPTER

TYPICAL



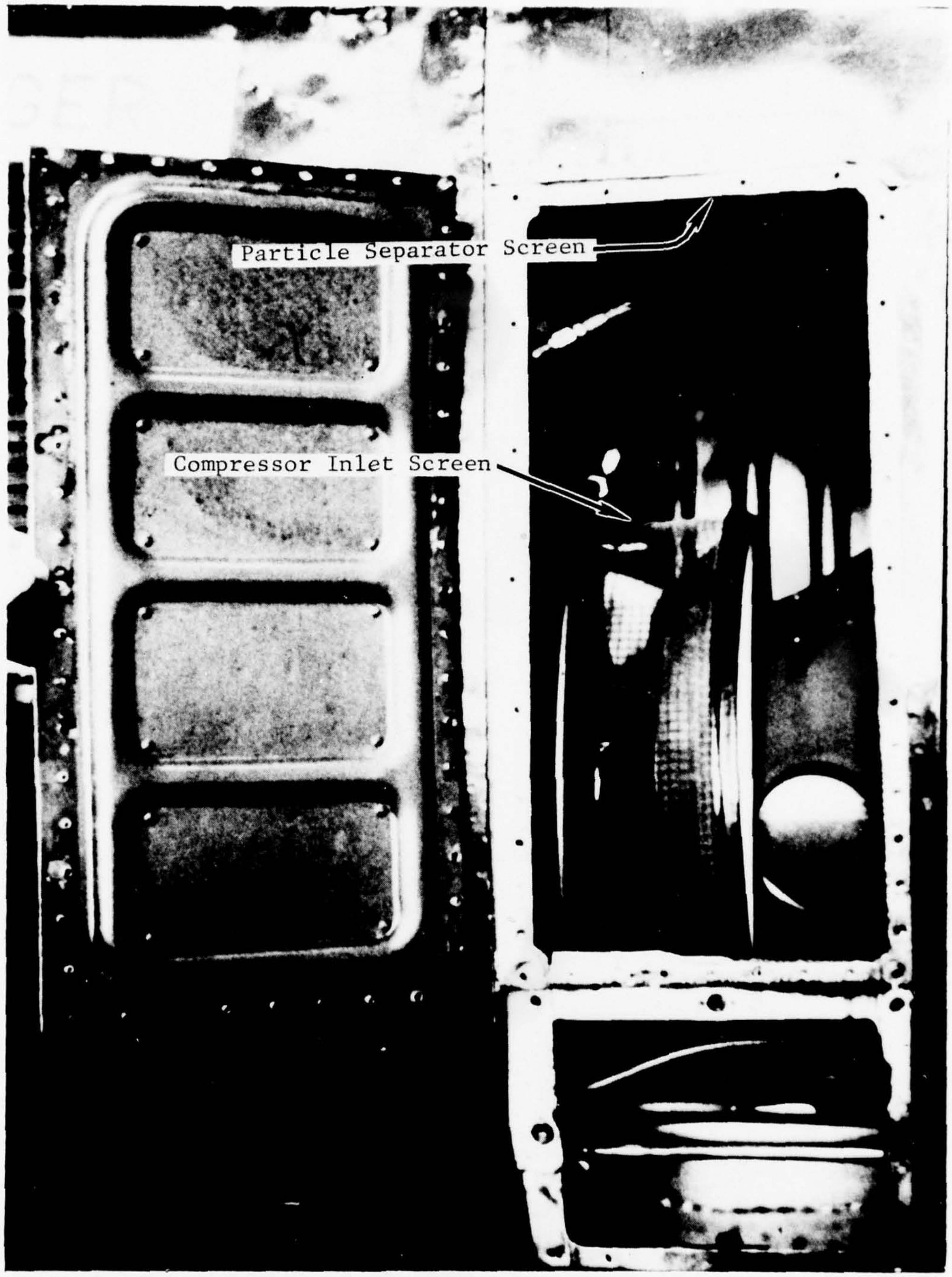


THE AH-1J TACTICAL HELICOPTER

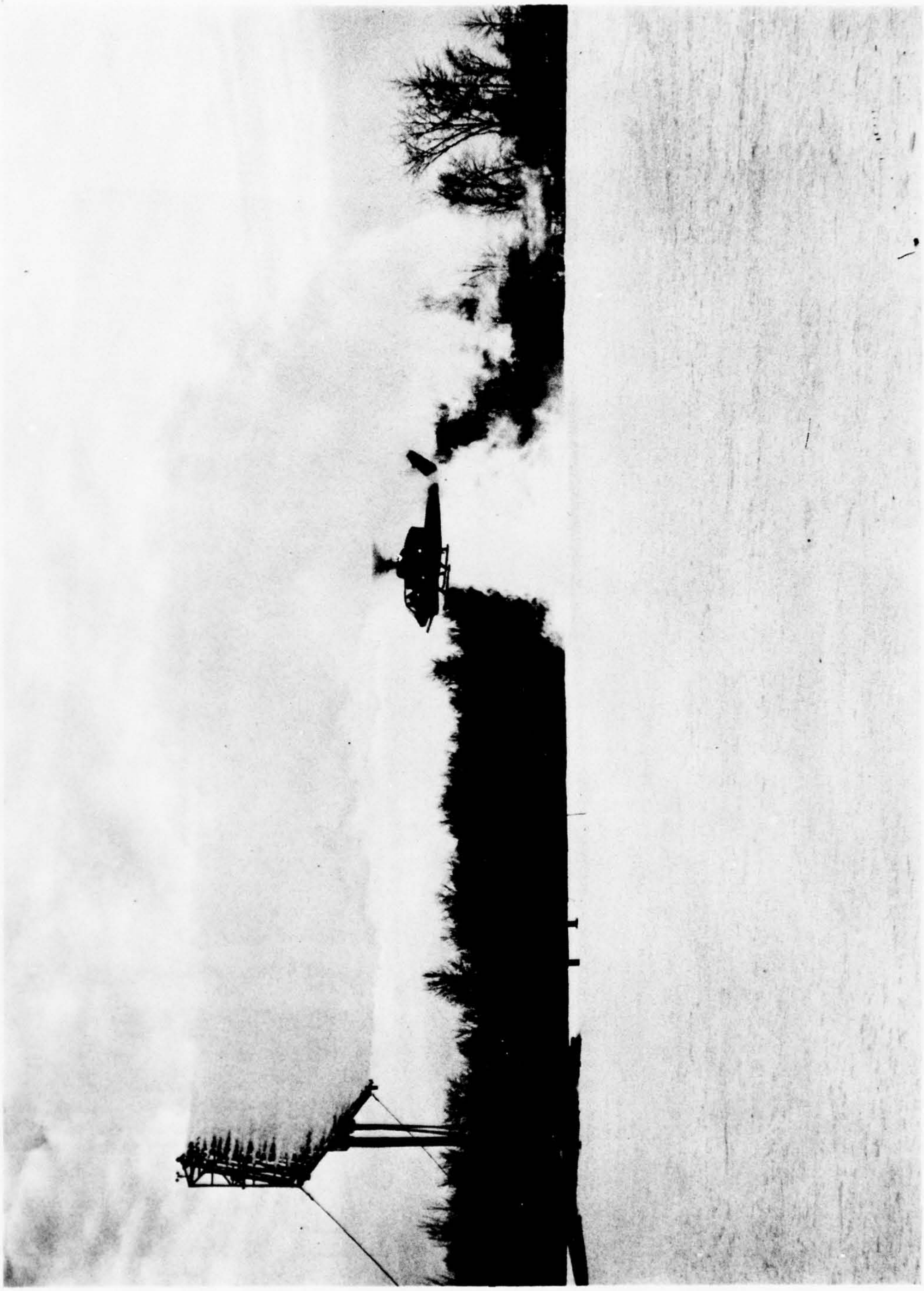


PROPULSION SYSTEM AIRFLOW DIAGRAM

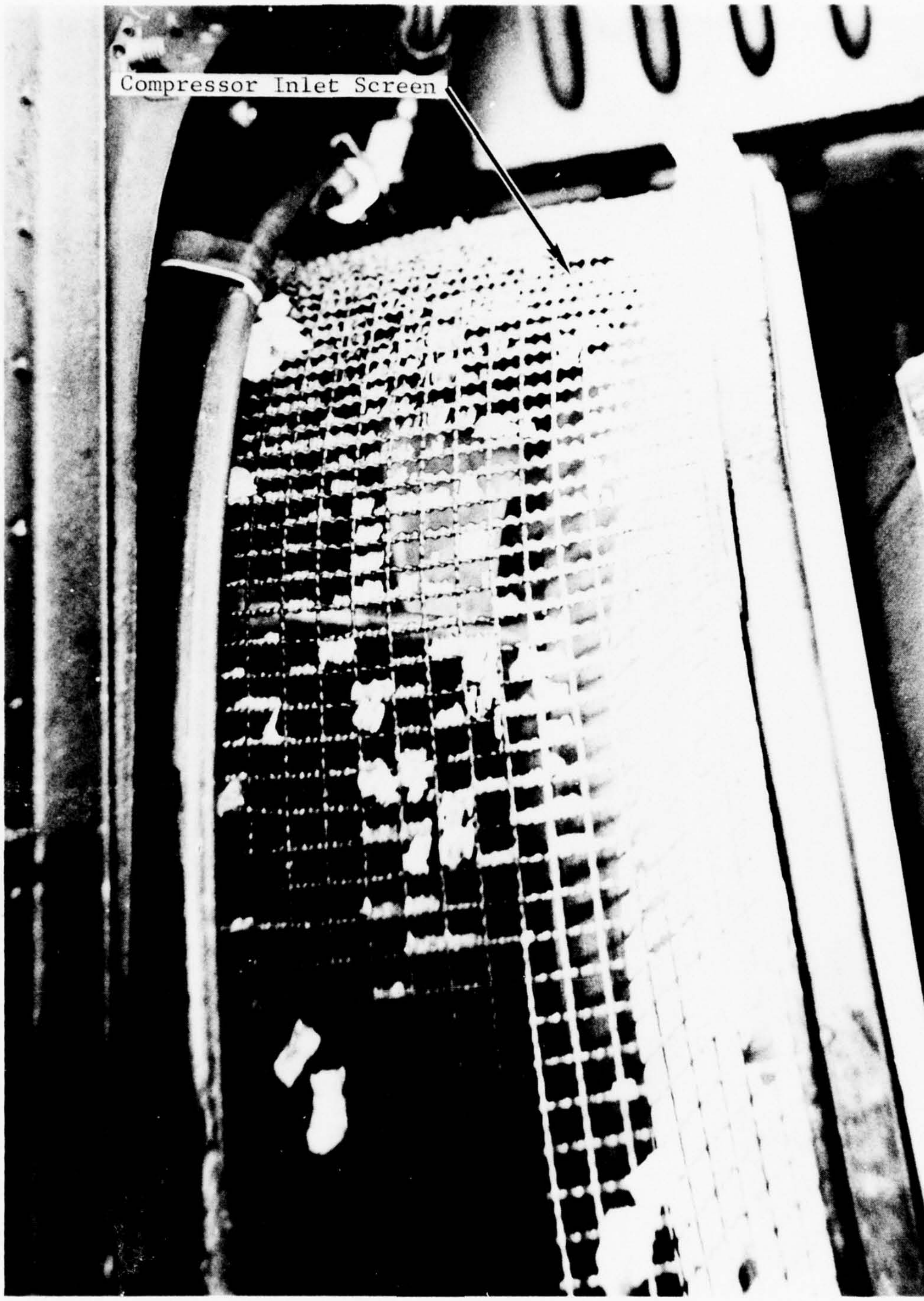
Enclosure (2)



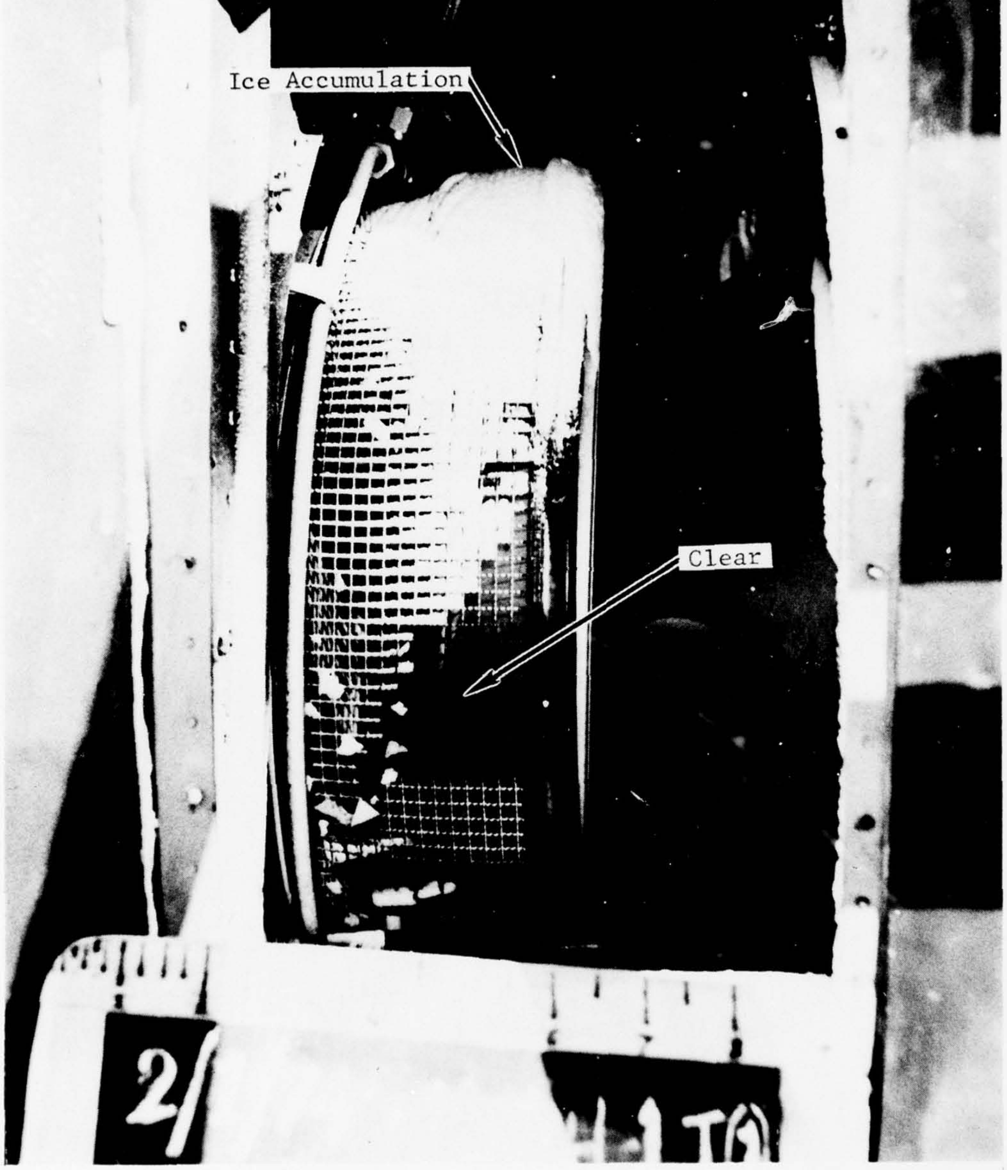
PROPULSION SYSTEM SCREENS



THE AH-1J HELICOPTER IN THE NRC SPRAY RIG ICING CLOUD

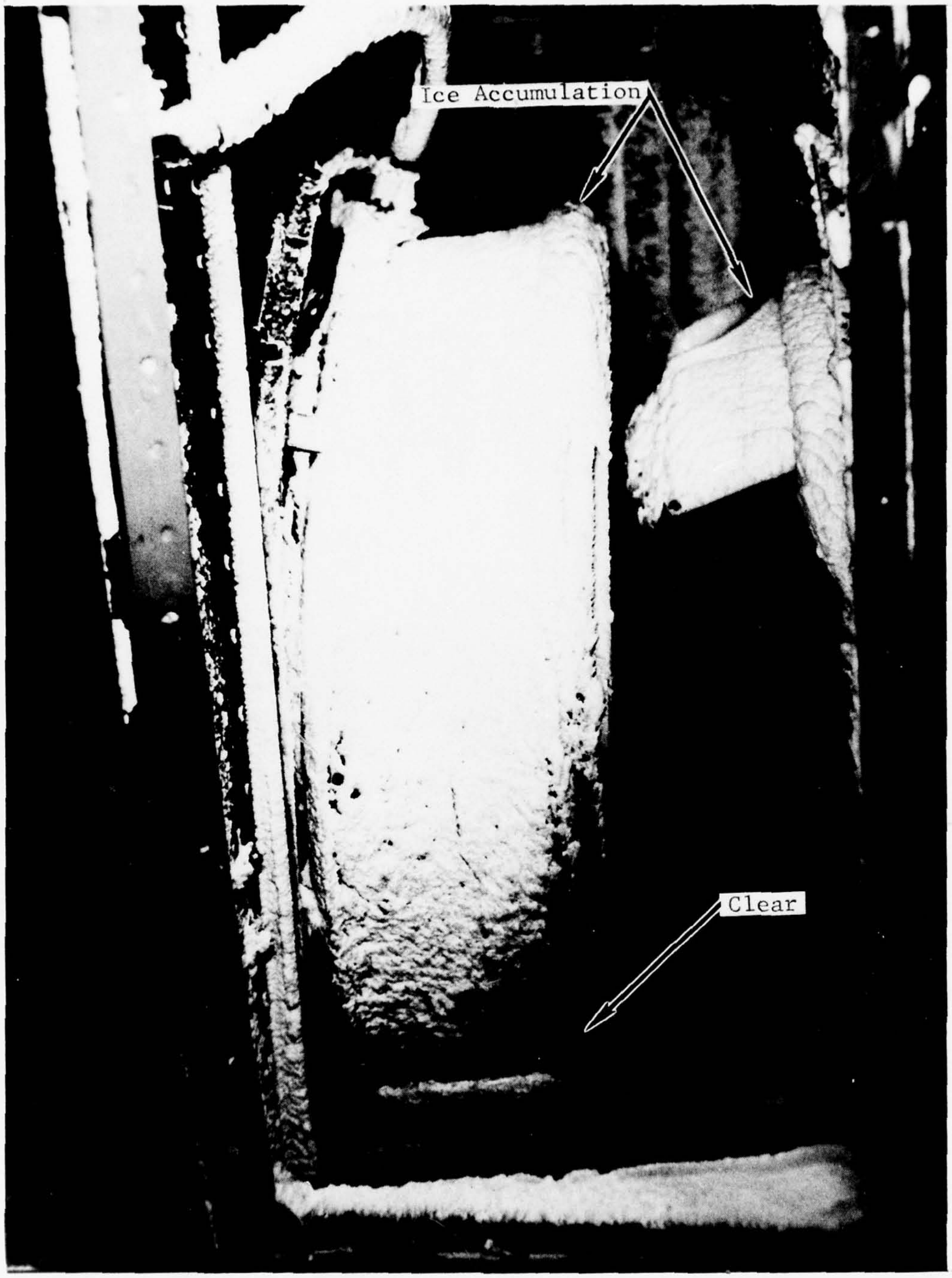


ICE ACCUMULATION ON THE COMPRESSOR INLET SCREEN
AFTER 60 MINUTES IN THE SPRAY RIG AT -4°C

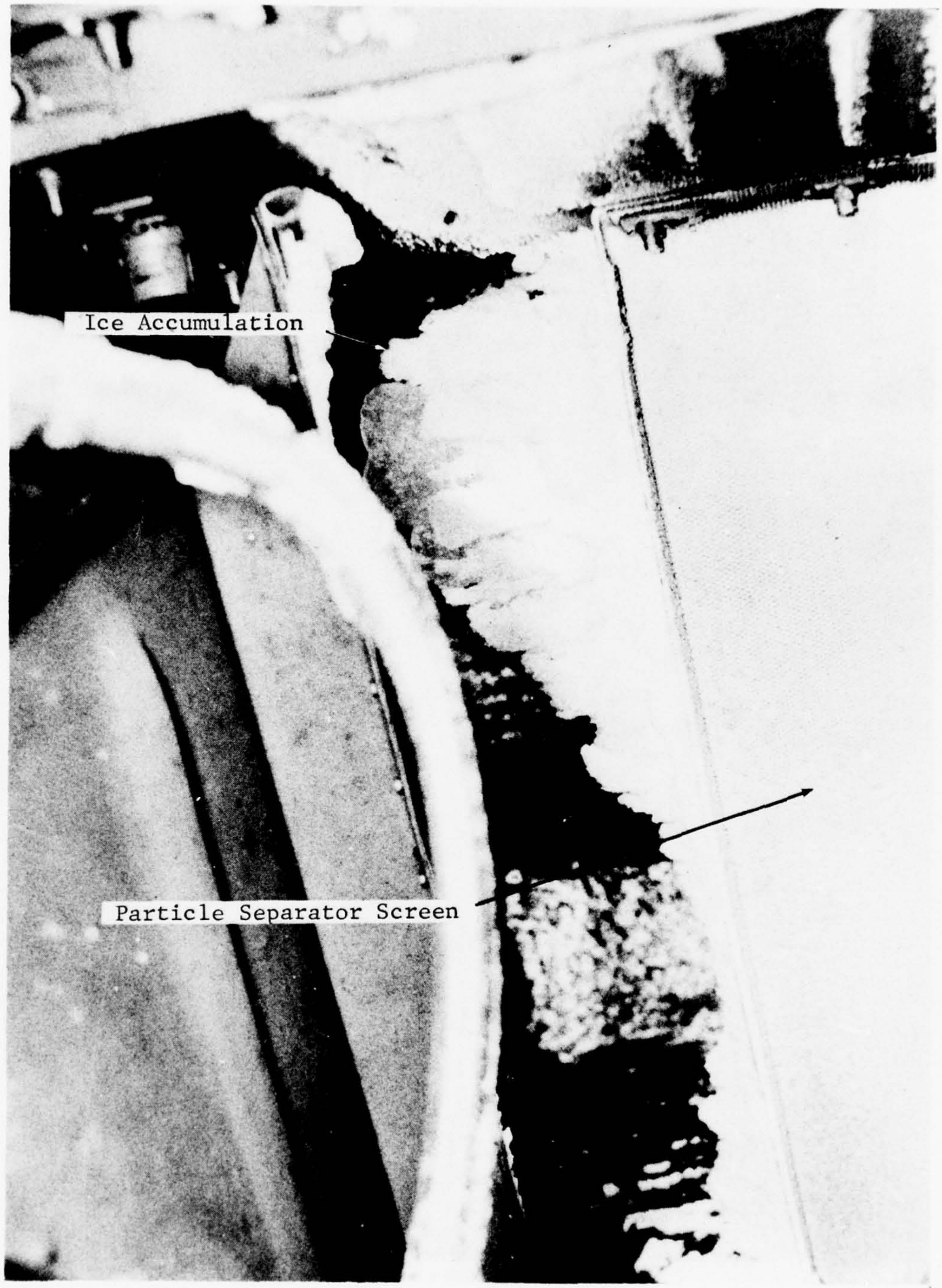


ICE ACCUMULATION ON THE COMPRESSOR INLET SCREEN
AFTER 60 MINUTES IN THE SPRAY RIG AT -16.5°C

ICE ACCUMULATION ON THE COMPRESSOR INLET SCREEN
AFTER 30 MINUTES IN THE SPRAY RIG AT -20.4°C



ICE ACCUMULATION ON THE COMPRESSOR INLET SCREEN
AFTER 58 MINUTES IN THE SPRAY RIG AT -20.4°C



ICE ACCUMULATION ON THE PARTICLE SEPARATOR SCREEN
AFTER 60 MINUTES IN THE SPRAY RIG AT -15.1°C

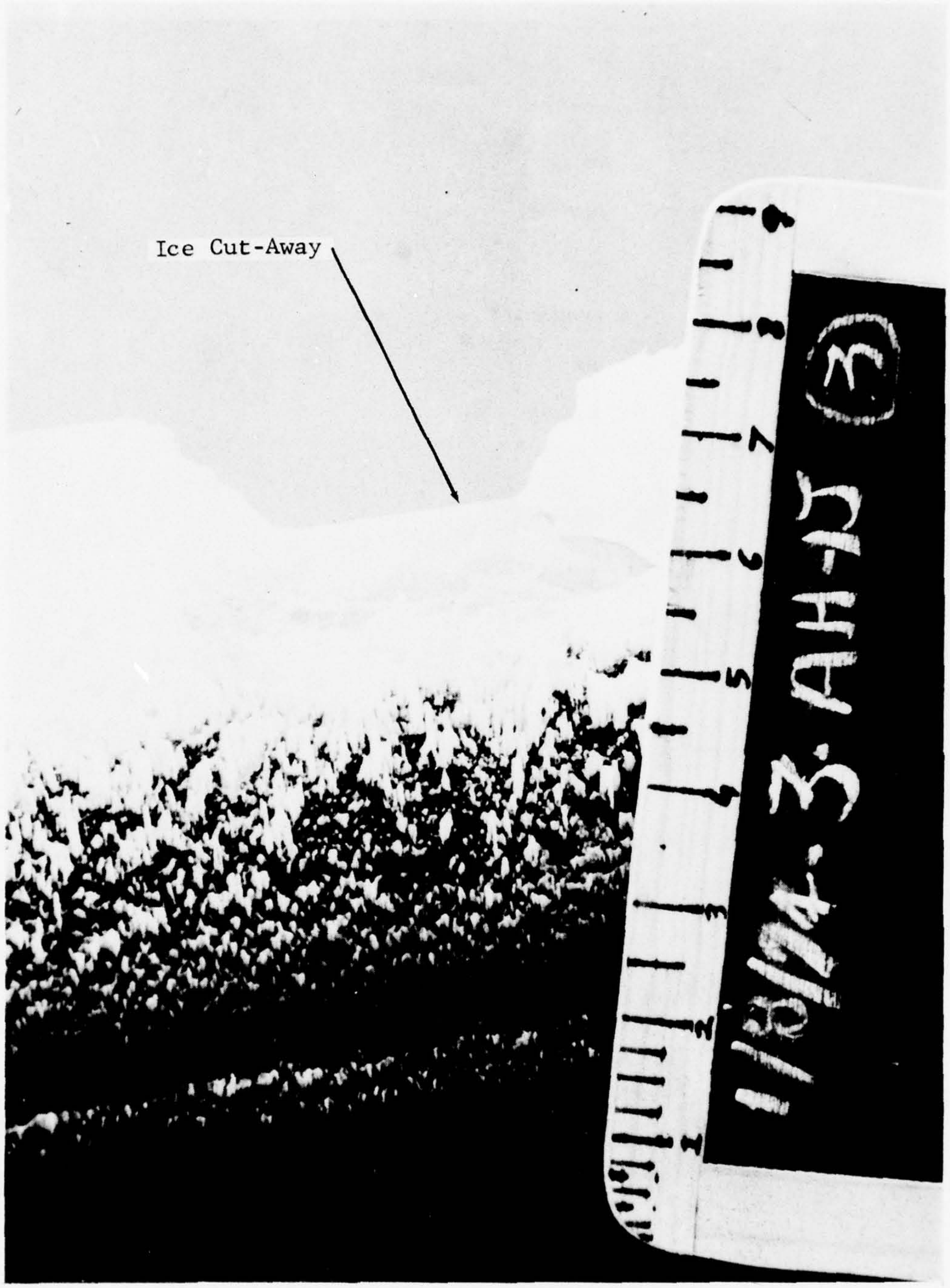
ICE ACCUMULATION ON THE PARTICLE SEPARATOR SCREEN
AFTER 60 MINUTES IN THE SPRAY RIG AT -15.1°C

Enclosure (10)

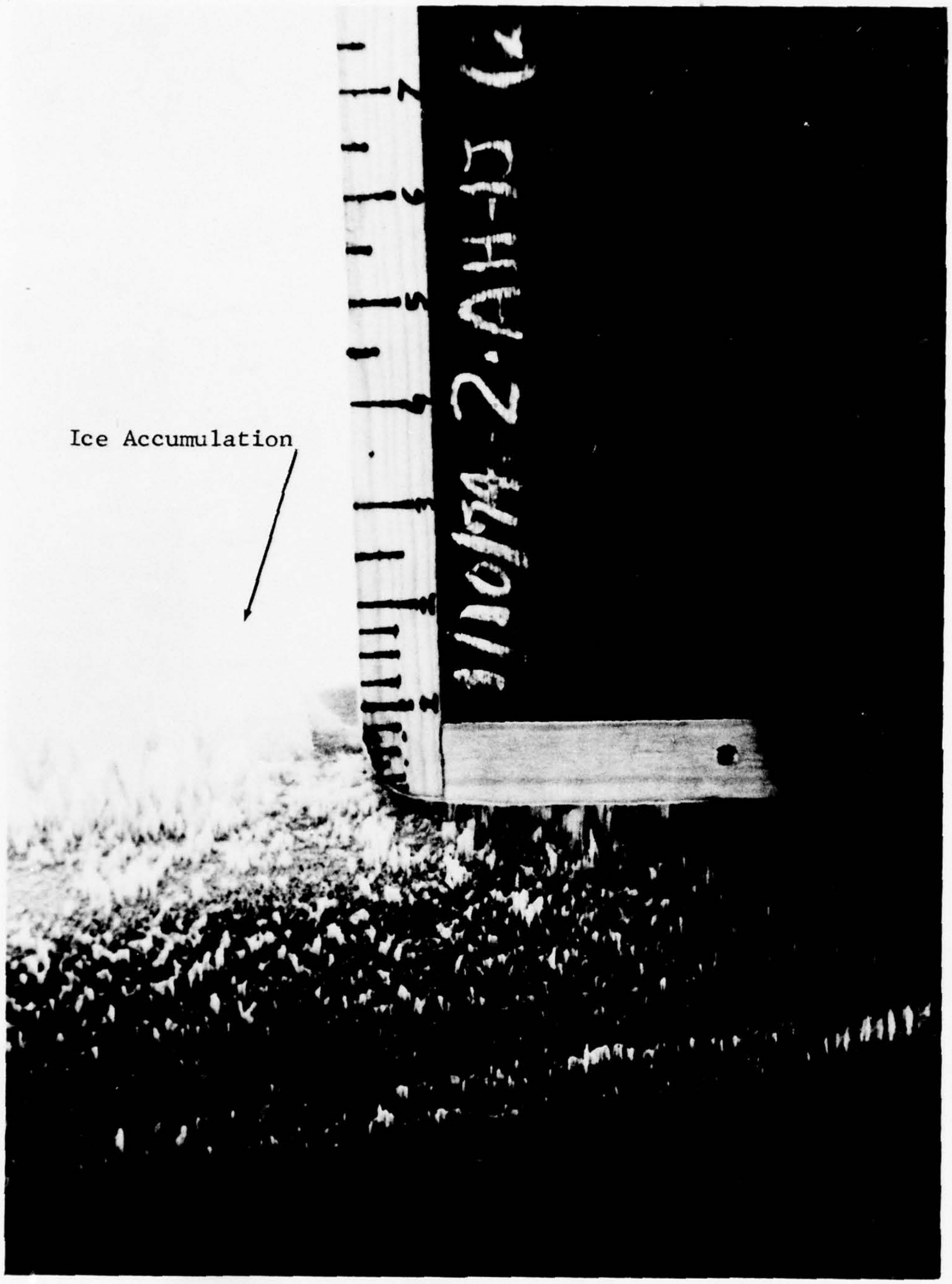
ICE ACCUMULATION ON THE ENVIRONMENTAL CONTROL UNIT SCREEN AFTER 60 MINUTES IN THE SPRAY RIG AT -4.0°C

ENCLOSURE (11)

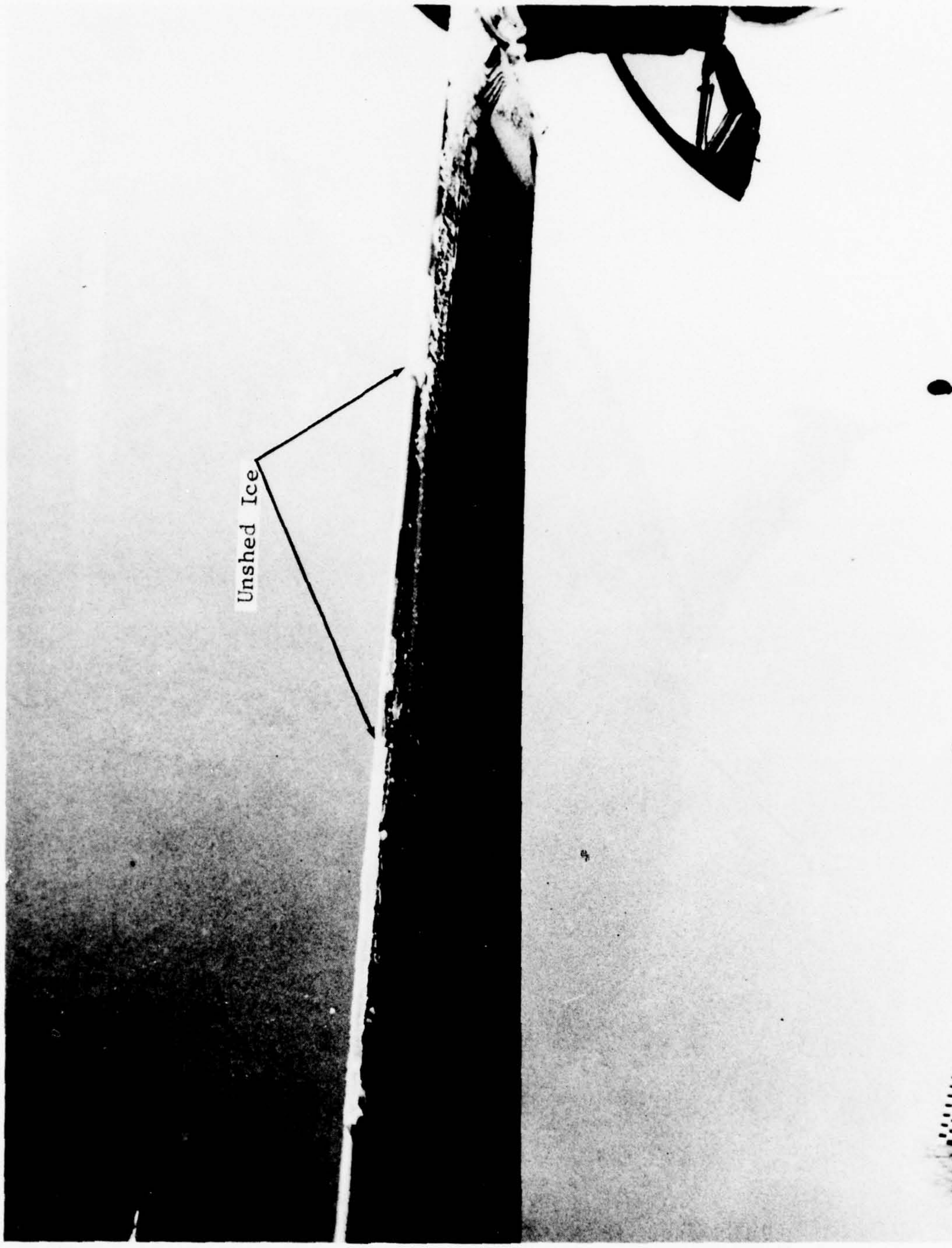
ICE SHEDDING CHARACTERISTICS OF MAIN ROTOR
BLADE ROOT AFTER 60 MINUTES IN THE SPRAY RIG AT -4.0°C



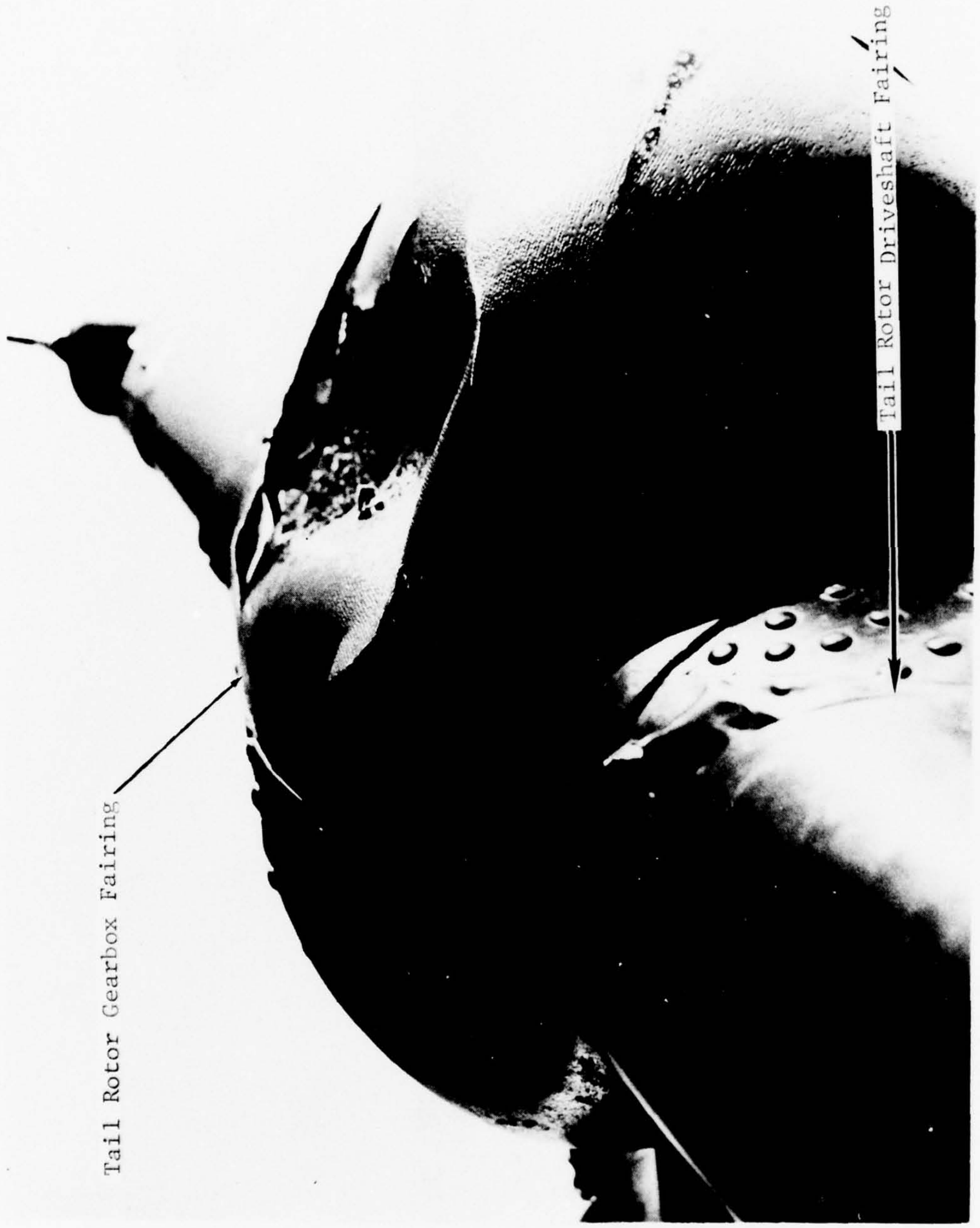
ICE ACCUMULATION ON THE MAIN ROTOR BLADE
AFTER 20 MINUTES IN THE SPRAY RIG AT -19.0°C



ICE ACCUMULATION ON THE MAIN ROTOR BLADE
AFTER 20 MINUTES IN THE SPRAY RIG AT -14.5°C

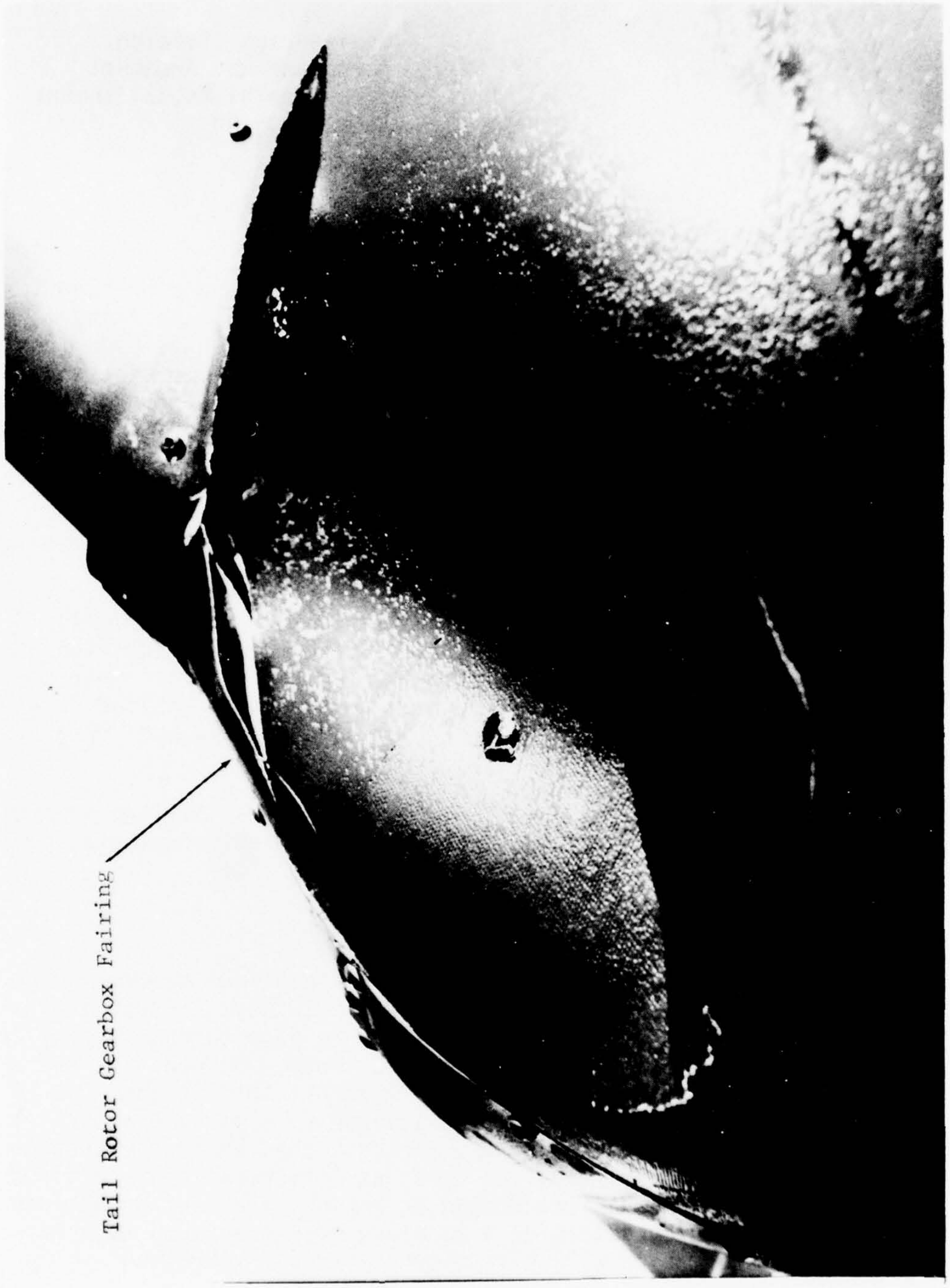


ICE ACCUMULATION ON THE MAIN ROTOR BLADE
AFTER 60 MINUTES IN THE SPRAY RIG AT -16.5°C



DAMAGE TO TAIL ROTOR GEARBOX FAIRING FROM MRB ICE SHEDDING DURING SHUTDOWN AFTER 60 MINUTES IN THE SPRAY RIG AT -16.5°C

ENCLOSURE (16)



DAMAGE TO TAIL ROTOR GEARBOX FAIRING FROM MRB ICE SHEDDING DURING SHUTDOWN AFTER 60 MINUTES IN THE SPRAY RIG AT -16.5°C

AIRCRAFT ICING PROBLEMS

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INTRODUCTION

It has always been a difficult if not an impossible problem to test an aircraft sufficiently to ensure that all the icing conditions in which it can or cannot safely fly have been identified. Equally, it has often been difficult to determine what modifications are required to improve the ability of an aircraft to stand up to icing conditions. This is because although icing conditions occur sufficiently often in certain areas at recognised times of the year to present a serious problem to the free operation of an aircraft, they are also so infrequent and so variable that it is very hard to find the appropriate natural icing condition when an aircraft is ready to be tested.

When faced with this sort of situation a test engineer will consider methods of simulating the difficult test condition and as you know several ways have been tried to do this. None of these methods is yet approaching perfection when applied to a whole aircraft although most of them have enabled some progress to be made in this field.

To see why it has taken so long to achieve this limited amount of success it is worth having another look at the fundamental problems of aircraft icing.

EFFECTS OF ICING CONDITIONS

Aircraft icing can have a serious adverse affect on the performance of an aircraft in at least four main ways. First ice can cause a mechanical obstruction either to flow through a pipe or a duct or to vision through a transparency. Second, ice can so modify the profile of part of the aircraft that it can ruin its aerodynamic efficiency. Third, ice can so alter the natural frequency of some parts of the aircraft that serious vibration can be induced. Lastly, ice that has formed can break off and cause serious mechanical damage or engine flame out or produce an asymmetric condition on a rotating mechanism such as a helicopter rotor which will give rise to serious vibration.

The first three conditions happen progressively although the deterioration can be very rapid. For instance a windscreen will

ice over in a reasonably small number of seconds while the final change to resonant frequency can also happen very quickly. Similarly high torque increases have been experienced within a minute of entering some icing clouds. The fourth condition may happen very suddenly and usually there is no warning as to when it is going to occur. Because of these potential hazards, several of which could easily cause the loss of an aircraft, flight testing in icing conditions either natural or simulated, has got to be approached with considerable caution. A further factor that makes this more difficult is that it does not always require a large quantity of ice to cause engine flame out or damage and these have been experienced in quite light conditions in a comparatively short time. Similarly rapid torque rises have on occasion been experienced in some comparatively mild icing environments.

METEOROLOGICAL CONDITIONS

You all know that the most common way in which ice forms on an aircraft is when it flies through certain meteorological conditions. Two factors are necessary to produce ice on an aircraft. The part of the aircraft on which the ice will form has to be at a temperature below freezing and the water which is going to form the ice must be in liquid form. The most common way of meeting both these conditions is for the aircraft to fly at a height where the ambient temperature is below freezing, through a cloud that is composed of liquid water droplets that are supercooled. Small cloud size droplets are quite commonly found in the supercooled state in relatively new clouds and they are capable of remaining liquid down to quite low temperatures. In the laboratory it has been possible to supercool water in droplet form down to -40^{o} but in natural clouds it is unusual to find supercooled water at temperatures much below -30^{o}C (-22^{o}F). A supercooled water drop is in an unstable state which it only reached by having been cooled in a relatively gentle manner, so, if it should strike an aircraft it will start to freeze immediately.

A number of meteorological conditions are conducive to the formation of clouds of supercooled droplets but most have some form of up current in them. Figure 1 gives a general illustration of one way in which such clouds are formed. It represents 5 stages in the life of a cumulus cloud starting from the left. The atmosphere must be unstable, so that once the air starts to rise, in this case by being heated by the ground, it will continue to do so. As the air rises it gradually expands and cools so when it reaches the dew point it is no longer able to retain all the water vapour in solution and some of it condenses out on

to the many nuclei that are present in the lower atmosphere to form small droplets of liquid water. This is the start of the cloud. As the air rises further it continues to cool and more water is condensed out, some of it on to the original droplets causing them to grow in size.

As they continue to rise and grow, the drops will pass through the freezing level and become supercooled. As the air continues to rise the drop size and the liquid water concentration increase until, for very tall cumulus clouds, concentrations of 5 gm of water per cubic metre of air, or more, can be present.

I have talked about cumulus clouds as their whole life cycle is fairly short and the main principles are fairly easy to understand. Supercooled clouds are however built up in other ways. Where moist air is lifted and cooled to below freezing, as often happens in a normal frontal system, the same process will take place. Icing clouds several hundred miles long can be generated in this way. Similarly a cloud mass at temperatures above freezing may be carried horizontally into a colder area and become supercooled. Basically however supercooled droplets are only formed from liquid water at a temperature above freezing and once they have formed they have a limited life unless the generation process is sustained.

Although the conditions I have just been talking about represent the most common way in which ice will form on an aircraft they are not the only ones. Freezing rain can be a very dangerous condition in which the large rain drops will form ice over a considerable area of the aircraft.

Snow is another condition that may represent a hazard to a helicopter. There are virtually two forms of snow which affect an aircraft in different ways, these are wet snow and dry snow. Wet snow occurs when the temperature is close to freezing and at some stage may be a little above freezing. Usually the flakes are larger than in the case of dry snow and a handful can readily be converted into a snowball. This snow can adhere to aircraft surfaces and may cause trouble. Dry snow occurs when the maximum ambient temperature is several degrees below freezing level. It can reach the aircraft as precipitation or lying snow may be recirculated by the downwash of a helicopter rotor when landing, taking off or hovering close to the ground. This dry snow does not constitute an icing hazard in its own right but behaves in the same way as a cloud composed entirely of ice crystals.

Clouds composed entirely of ice crystals at temperatures below freezing were known to produce compressor stall on one type of

engine back in the 1950s but normally they will only produce ice on an aircraft if there is enough heat on some part of the airframe on which the crystals impinge to start to melt them. If there is enough heat to melt the crystal completely, the water will flow over the surface. Three things can then happen to it. Either it will blow off into the atmosphere where it will refreeze as an ice crystal, or it will collect in some part of the aircraft and may later freeze if the local temperature becomes low enough or it may flow on to a colder part of the aircraft where it will freeze and build up into a lump of ice that may become quite big. Later if the aircraft descends to a warmer atmosphere this ice formation will break off and may cause damage particularly if it goes into an engine. An alternative mechanism is when there is not enough heat to melt the whole ice crystal but there is enough to melt the part that is in contact with the aircraft. This will allow the ice crystal to flow on its own film of water and if it is then caught in some pocket of the aircraft structure, possibly in an engine intake, where the temperature is a little lower an accumulation of ice crystals can gather. Later, after some change in the flight conditions the ice crystals may come out as a concentrated mass and cause an engine flame out. This did happen many years ago in the Britannia aircraft and it took some time to solve the problem.

One last condition that can be the worst of all to some thermal protection systems is a cloud composed of mixed ice crystals and supercooled water. The supercooled water tries to change into ice in the normal way and it may help to retain the ice crystals on the heated surface long enough to allow them to start to melt. This requires latent heat to be supplied by the protection system in addition to the heat required to try to keep the surface temperature above freezing and some systems have failed to cope with the combined requirement.

BASIC THEORY

If we now have a look at the way in which the water gets to the various parts of an aircraft it will be seen that this is dependent on a number of factors including the shape of each component. Figure 2 represents diagrammatically the relative flow round a cylinder, of air and water drops. Apart from the stagnation line, the air streamlines all go round the cylinder but due to their inertia some of the drops in the path of the cylinder will not be able to avoid it. The drops inside the limits of catch will all strike the cylinder while those outside the limits will escape. This represents a single speed and a single size of drop. If the drops are larger the limit lines would be set further apart as the inertia of the larger drops will be greater so that a higher

proportion is caught. Similarly the size of the cylinder will affect the limit lines and the efficiency of catch, which is the ratio of the number of drops that strike the cylinder to the number of drops in the area through which the cylinder passes, increases as the cylinder becomes smaller. An increase of the speed with which the cylinder is passing through the cloud will increase the efficiency of catch and temperature has an effect as the density and viscosity of the air which determine the force that moves the droplets out of the path of the cylinder are dependent on this. The area of the cylinder which the drops will hit varies in a similar way. This can be quite important because on the leading edge of a rotor blade, the area of catch is comparatively small and it is only this area that needs protection. One of the effects of the high efficiency of catch of thin wires is that a fine mesh debris guard makes an excellent ice collector. Figure 3 shows what can be built up on the air intake of a piston engine which was fitted with such a guard. This of course was no problem to the aircraft as the engine could draw its air from a warm sheltered source when flying in icing conditions. Life is however not nearly so easy for a jet engine as it uses more air than a piston engine and so cannot benefit so much from an alternative intake. As so often happens this lesson was learned the hard way, when in 1951 a number of American F84s equipped with what were described as engine screens, encountered severe icing conditions over Eastern Indiana. 8 planes crashed within a 13 mile radius and four of the pilots were killed.

Having once reached a cold aircraft surface a supercooled water droplet will start to freeze. This is quite a complicated process as can be seen from Figure 4 which gives the heat flow equation for the icing surface of an unheated body and shows how each part of the equation operates

$$Q_f + Q_k + Q_i + Q_v - Q_w - Q_c - Q_e = Q_s$$

where Q_f = latent heat of fusion of impinging water

Q_k = kinetic heating by water droplets

Q_i = heat given up by ice cooling (from freezing to θ_s)

Q_v = kinetic heating from air

Q_w = heat required to raise water temperature from θ_o to freezing

Q_c = convective heat loss

Q_e = evaporative heat loss

Q_s = conductive heat loss from surface

θ_o = ambient air temperature

θ_s = icing surface temperature

Probably the most important factor is the first one the latent heat of fusion but each of the positive parameters contribute heat which must all be dissipated before the water will freeze completely. As Q_f for 1 cc of water is 80 calories and the Q_w to warm up 1 cc from -10°C to 0°C is only 10 calories there is obviously a fair amount of heat to be dissipated by convection, conduction and evaporation. For a large drop this will take an appreciable time especially if the temperature is not very much below freezing. During the time it takes to dissipate all this heat the unfrozen part of the drop will flow over the surface of the aircraft until the whole drop has finally frozen. Usually because it was a large drop it would come from a cloud containing a large number of drops and the next drop to strike the same area will arrive before the first one has completely frozen. In this way the layer of ice that builds up will be a clear well-knit sheet. This type of ice is called glaze or clear ice. At the other end of the scale the droplets at low temperatures are usually smaller and the concentration lower. The drop will therefore freeze much more quickly and will flow very little during the process. The next drop from the cloud is unlikely to land in the same area until after the first drop has completely frozen. In this way air will be trapped between the frozen drops and the ice will have a white appearance. Its shape will be very different from that of glaze ice. This type of ice is called rime ice. Between these two extremes there is a wide variety of combinations of ice both in texture and shape. Figure 5 illustrates the range of shapes that can build up on a thin strut depending on the temperature and the concentration of water. On the top row the water all flowed from the point of impact at the leading edge before starting to freeze. With slightly lower temperatures the ice formed at the leading edge and flowed sideways as well as backwards to form the horrible aerodynamic shapes you can see. At the bottom where the temperature is low the ice formation may even improve the aerodynamic characteristics.

What happened to the water on the top row is important. When the water content is increased, the sum of the positive parameters in the heat flow equation becomes larger while the sum of the negative factors is reduced when the air temperature comes nearer to freezing. The effect of this is to raise the surface tempera-

ture and when this reaches freezing, a fraction of the water runs back as seen on the top row. If even more heat is available, the surface temperature does not rise beyond freezing while ice is still forming, but more water runs back. Dr Ludlam who first defined this phenomenon started with the case of a cylinder that was completely covered with ice when it was rotated in an icing atmosphere. On such a cylinder the water that ran back would be blown off so that the amount of water that froze would be less than the amount of water that landed on the cylinder. As measuring the amount of ice that forms on a surface is the mechanism used by several icing meters, this phenomenon is important as such instruments may become quite unreliable at high concentrations and high temperatures. The point where such run back starts has become known as the 'Ludlam Limit'. When the whole surface of a strut is not covered with ice, the leading edge where there is direct impingement by the water drops is the only part where the temperature is controlled by the parameters in the heat flow equation. Further back there will be less heating so the temperature will be low enough to allow the water to freeze. On a large strut or a helicopter rotor blade the water will almost always freeze well before it gets very far from the impingement area.

The same sort of mechanism is responsible for so called 'run back' ice forming behind an impingement area that is heated. A good hot area can evaporate all the water that lands on it but if the heat is insufficient to do this then water will run over the surface of the heater and beyond. If the temperature behind the heater is low enough, the water will freeze before it reaches the end of the surface and blows off. This may or may not be important depending on whether this ice has any adverse effect on the performance of the helicopter or whether it may be hazardous if it breaks off. The equation I showed only deals with liquid water reaching a surface. If we take the process a stage further and consider a cloud of mixed ice crystals and supercooled water, there are additional factors to add if the temperature of the surface is high enough to start to melt the ice crystals. Heat has to be supplied to raise the temperature of the part of the ice crystal in contact with the surface from its ambient temperature to freezing and further latent heat has to be supplied to melt the crystal. Having to supply this extra heat over and above what was required for dealing with the liquid water may well prevent the heated protection system from evaporating all the ice and water that lands on it and so run back ice may be formed.

One of the requirements for ice to form on an aircraft is that the surface temperature must be below freezing. This does not

automatically happen if the air temperature is below freezing. In flight, as you know, there is an increase in the temperature of the aircraft surface above ambient due to kinetic heating. This means that ice could not form until the air temperature is low enough to bring the skin temperature down to freezing. This is quite straightforward in dry air but when liquid water is present it has a considerable cooling effect and the kinetic heat rise is reduced by roughly a half. When ice crystals are also present there is an even greater cooling effect which can sometimes virtually wash out all the kinetic heating. The reason that ice crystals can have this effect is that when they land on a warm surface and do not bounce off immediately, they start to melt and here the latent heat required has to be supplied from the aircraft.

SIMULATION METHODS

All this theory identifies the three most important factors governing the formation of ice as Liquid Water Content (LWC), droplet size and temperature. These factors can all be controlled to make an icing cloud. Water can be forced through a nozzle and atomised into drops of something like the same size as would be found in a cloud. The Liquid Water Content can be controlled by choosing the right number of nozzles and by adjusting the water flow through them. Air temperatures can be controlled in a refrigerated tunnel or the ambient air may be used either on the ground or at an appropriate altitude in flight. Using these principles several artificial icing test facilities have been made.

SIMULATION FACILITIES

Probably the first type that has now been widely used for well over 25 years is a tunnel to test engines in simulated icing conditions. Almost all current jet engines are now adequately protected from classical icing conditions as a result of tests in tunnels of this sort. The next stage after protecting the engine is to protect the air intake. This has proved to be a much more difficult problem and very few satisfactory solutions are yet available. This is partly because few if any engine intakes were originally designed to cope with icing conditions, the designer being much more concerned with optimising performance. Many designs were very difficult to protect and the test facilities that were suitable for engines were often too small to accommodate the intakes. In addition the intake/engine combination is vulnerable to ice forming anywhere upstream of the engine either in or in front of the intake, and breaking off to cause damage or flame out. Some larger tunnels have been used to

improve these intakes and you will hear more about this in a paper tomorrow afternoon.

The next artificial icing facility aimed specifically at testing helicopters is the NRC spray rig in Ottawa. This was started nearly 20 years ago and is probably best illustrated in this short film. Some 160 nozzles are mounted on a frame 75 feet wide and 15 feet deep. The whole frame can be raised on a mast some 70 feet high and the icing cloud from the nozzles is blown over a hovering helicopter by the ambient wind. A large number of helicopters have used it since it was started and very useful preliminary information has been obtained. It can of course only deal with hovering flight but this has nevertheless been sufficient to show up a number of problems that have had to be corrected before flight into natural icirg conditions could be contemplated.

Icing tankers to test fixed wing aircraft in simulated icing conditions in flight were developed about the same time as the spray rig but were not used for helicopters till some time later. A C130 icing tanker which can fly sufficiently slowly to suit helicopters has now been in use for several years. More recently a CH47 helicopter has been adapted as an icing tanker and was used on trials in Alaska last winter. As you will hear tomorrow quite a lot of simulated icing testing can be done in the Climatic Hangar at Eglin.

One other facility is the Blower Tunnel at my own Establishment at Boscombe Down in England. This tunnel which was built about 30 years ago was modified a few years back to give an artificial icing cloud. In the Blower Tunnel a stream of air is propelled by four contra-rotating fans driven by four Merlin engines, through a suitable nozzle. Nozzles of diameters from 8 feet down to 2 feet are available and these control the maximum air speeds from 180 knots up to 350 knots. The area in front of the tunnel is large enough to accommodate any aircraft and a large number of lashing down points are provided. When being used as an icing facility, liquid nitrogen is injected into the airstream and cools it down to well below the ambient temperature. The amount of cooling depends on the velocity and diameter of the airstream but with the maximum flow of 2000 lb per minute for the 4 feet diameter nozzle at 100 knots, a temperature of 30°C (55°F) below ambient can be achieved while with the 6 feet diameter nozzle at 200 knots only 8°C (15°F) below ambient is possible. Figure 6 shows the cooled airstream from the blower tunnel being blown over a test specimen mounted on a frame. The pattern of lashing down points is clearly visible. Because the air is cooled to well below the ambient temperature the air in the jet

is saturated and because the working temperature is always below freezing the moisture that has been condensed out from the atmosphere normally freezes into small soft ice particles. These make the stream completely opaque but in most circumstances appear to have no other adverse effect. To form an artificial icing cloud, water is sprayed into the airstream from a series of atomising nozzles.

ADVANTAGES OF SIMULATION

There are obviously a number of advantages in being able to make tests in simulated icing conditions. To start with it is at least possible to make the tests when you want to and, within the capacity of the facility, to test under any combination of LWC, temperature and droplet size that is wanted, for as long or as short a time as required. Test conditions can also be repeated at will. In the groundbased facilities it is possible to make a rapid visual check of how much ice has built up where and to examine any other aspects such as the performance of any protection system. This is obviously a great deal safer than flying through uncontrolled conditions.

One phrase I just used is rather important and that was 'within the capacity of the facility'. So far as straight engine protection against classical icing is concerned the facilities used appear to have been adequate to cover all the conditions required to clear the engine. Some of the larger facilities have not always been quite so successful when it comes to other aspects of the helicopter. On most of them some limitation has prevented the complete helicopter from being immersed all the time in a uniform cloud with the correct LWC and droplet size. To understand why this is we should look at the calibration of some of these facilities. Before doing this we must consider the types of instruments that are available to make the necessary measurements either in artificial or in natural icing clouds.

ICING INSTRUMENTATION

The measurement of air temperature in icing conditions introduces special problems. This is because ice actually forming on a thermometer bulb is giving up latent heat of fusion to the bulb and later when a layer of ice has been formed it provides partial insulation to the bulb that will reduce its rate of response. These problems can be overcome by shielding the thermometer bulb from the impingement of cloud droplets but the shield will probably affect the recovery factor and so the complete installation has to be calibrated before use.

The type of instruments that have been used to calibrate simulated icing clouds and to measure natural icing conditions have been of two main types. For measuring LWC the instrument has either allowed ice to form on it and then some technique has been used to deduce the concentration, or the instrument has sensed the impact of the cloud droplets, usually on heated elements, and has deduced the concentration by some electrical circuitry. The first largely successful instrument of the ice accretion type was the multi rotating cylinders. Here several cylinders of different diameters were exposed simultaneously to the icing condition and rotated to allow a uniform layer of ice to be formed. After sufficient ice had formed, the cylinders were withdrawn and usually stored so that the amount of ice that had been collected on each cylinder could be measured in the laboratory normally by weighing. Because of their difference in diameter each cylinder had a different catch efficiency so it was possible to calculate both the LWC and the droplet size by feeding in all the known parameters into standard equations and using a graphical analysis. The work was somewhat tedious and apart from various practical difficulties the accuracy was not always high. In particular when the temperature was fairly close to freezing there was a thermodynamic limitation to the capacity of the method as not all the water had time to freeze before it was blown off. Another accretion type of instrument was the rotating disc which allowed ice to build on the edge of a thin disc 2 ins in diameter revolving at about 2½ rpm. The catch efficiency was high and the ice was measured by a spring loaded feeler and later scraped off to present a clean surface when this part of the disc had revolved back into the catchment area. This at least gave a continuous record of the average ice thickness over a short period although it suffered from the same problems of blow off at temperatures near freezing. A refrigerated version of the rotating disc was tried to overcome this problem with limited success. A more recent design of accretion meter is the Rosemount detector where the ice build up changes the natural frequency of a small vibrating rod and so gives warning of the presence of icing conditions. By measuring the time required to change the frequency by a given amount it is possible to obtain a measure of LWC.

The other type of ice detector sometimes known as the 'inferential type' may be illustrated by the Johnson Williams or the Normalair-Garrett types. The basic principle is that a heated element is exposed to the atmospheric conditions and a second element, shielded from direct impingement of cloud droplets but otherwise influenced by speed and atmospheric conditions, is used to balance all effects other than the impingement of the water. The cooling of the exposed element caused by the water

is measured and converted to a reading of LWC. The Johnson Williams instrument uses wires about 60 thou thick as the sensing element while the NGL instrument has elements about ¼ inch thick. Both instruments have been used successfully in measuring artificial and natural icing clouds although various users have experienced problems with both of them.

Droplet sizes have been measured by one or two different capturing techniques. Oiled slides where a small slide has been coated with a film of a suitable oil have been exposed for a very short time to catch cloud droplets and been photographed almost immediately in a micro camera. The right type of oil has to be used to prevent evaporation of the drops between collection and photography and there is a top speed limitation above which the oil film is blown away by the airflow when collecting the drops. Several other precautions have to be observed but the system has been used successfully for some 25 years or more and it does collect the actual cloud drops. A second system that has the advantage that immediate photography is not required is where a slide is coated with gelatine and is exposed to the cloud. The cloud drops striking the slide leave a permanent mark on the gelatine film the size of which is a measure of the drop diameter. This slide can be photographed at leisure and stored for an almost indefinite period both before and after exposure. These more direct methods have largely replaced the rotating cylinder method of measuring drop size.

With the advent of Laser Holography and other similar techniques more sophisticated methods of measuring both drop size and LWC are being developed. One system sizes and counts each drop as it passes through the measuring area and can then calculate both LWC and median drop diameter. When such instruments are readily available for airborne use it will represent a great advance in this type of testing. Until this happy time arrives we have to put up with the instruments that are available now. Most of these were developed for fixed wing aircraft where a reasonably smooth constant flow could be assured. The airflow round a helicopter varies considerably from hover to cruising flight and it is very difficult to find a suitable spot to mount any of these instruments some of which are quite unsatisfactory at speeds as low as the top speed of some helicopters. For the British helicopter icing trials over the past 6 years that will be described by Mr Wilson tomorrow afternoon, the most useful ice detector has been a short rod mounted outside the pilots cockpit on which the ice built up. It was in fact one of the old fashioned 'hot rods' that have been used on a great many commercial airliners for many years. It has the great advantage of being simple and gave a direct indication of the type of

icing condition that was being flown through. Many other types of ice detectors have been tried, all of them with some success but also all of them with some problems not all of which have yet been overcome.

CALIBRATION METHODS

For the calibration of an airborne simulation facility it has been usual to fly a fixed wing aircraft equipped with suitable instrumentation in the artificial cloud. An inferential type of ice detector usually a Johnson Williams or a Normalair-Garrett (which used to be known as a Teddington Indicator before the firm was bought up) has been used to measure the LWC. Either oiled slides or gelatine coated slides have been used to measure the drop size. Ambient humidity has also been recorded either by the tanker or by the calibration aircraft as this can affect the performance of the cloud especially further from the nozzles.

In the early days drop size was also estimated by how much of the nose of a drop tank at the wing tip of the calibration aircraft was covered by ice. This gave a good indication of the way in which the icing from the artificial cloud would cover any aircraft under test. Sometimes the air temperature was measured on the tanker aircraft to avoid the need for a shielded probe but on at least one calibration aircraft a shielded probe was used.

CALIBRATION RESULTS

Two unhappy results came out of the calibrations of some of these airborne tankers. As might be expected the water concentration was highest at the centre of the cloud and reduced towards the edge but this change in concentration was sometimes much more rapid than would be hoped for. The second was the size of the water droplets which should sometimes have been of the order of 15 to 20 microns to meet the smaller end of the international regulations. These were seldom much less than 40 microns when measured as a volume median diameter and in some cases could stray up as far as 80 microns or so. There are two obvious potential explanations for this change in drop size. Some evaporation from the water drops is bound to happen as the relative humidity in the clear air that is always used for such tests is below 100%. The rate of evaporation is different for different size drops as the smaller ones evaporate more quickly. If the airflow is at all turbulent there is a good change of larger size drops being produced by collisions between smaller ones. Such collisions could also cause supercooled drops to form into ice crystals. Most of the atomising nozzles that have been used tend to produce larger drop sizes with larger water flows so although

this is probably in line with what happens in nature it makes things difficult when one is trying to simulate a constant drop size.

The other large ground facilities such as the NRC spray rig and the Boscombe Down Blower Tunnel suffer from similar problems. In the NRC rig the cloud is blown by the ambient wind and this does not produce great turbulence until the wind speed becomes very high. It is therefore less likely to suffer from drop collisions than the Blower Tunnel where the airflow is much faster and so likely to be more turbulent. In fact the main factor that increases the drop size of the NRC Rig above 20 microns is when the amount of water passing through each nozzle has to be increased to give a higher LWC. In the Blower Tunnel it has been possible to keep the drop size down to 20 microns but only for a limited distance from the spray nozzles.

In passing, it is worth mentioning that for calibrating the LWC of the NRC spray rig, the amount of ice that builds up on the leading edge of a rotor blade in a given time is one of the methods used. Drop size is checked by oiled slides. The methods used in the Blower Tunnel are the same as for an airborne tanker, a Johnson Williams moisture meter and oiled slides.

VALUE OF SIMULATION

The final question to answer is how well these various simulation facilities compare with the natural icing environment. We have seen from calibration results that the correct LWC can be achieved although the even-ness of its distribution depends on the airflow in the facility. Most closed tunnels should be satisfactory while open facilities with the possible exception of the NRC spray rig become worse the further the test specimen is from the nozzles. The control of temperature seldom presents much of a problem although when ambient air is used the existing temperature has to be accepted. Drop size has been more difficult to control in all facilities and in the larger open ones it has been especially poor.

Fortunately there are some occasions when drop size is not a very important factor for instance when the main aim of the test is merely to build up a certain amount of ice on a test specimen to see how it behaves. If the drop size is too big the efficiency of catch of any test specimen will be increased so more ice will be collected in a given time which merely shortens the test. The area of catch will also be increased but this may or may not be important depending on the object of the test. If if is not important then all that is done is that the test has

been a little more severe than was required. On the other hand there are a number of occasions when it is very important that the drop size is correct. If for instance the airflow has to go round any bends then the centrifugal action on the drops is very dependent on size and the question of whether or not ice will form on the wall of the bend is almost entirely dependent on this factor together of course with the temperature of the wall. The other type of occasion when drop size should be right is when the area of direct impingement is important.

Despite these problems the types of ice that are obtained by simulation techniques can be the same as several of the types of ice that are produced in natural clouds. There is of course a very wide variety of ice formations that can occur naturally but various observers who have experience in the icing field have confirmed that a number of the shapes and textures they have seen produced by simulation facilities correspond reasonably with those of ice built up in natural conditions.

The systematic comparison of artificial and natural ice formations has still a long way to go and the present areas of agreement are still fairly limited. There is however no doubt that, provided they are used intelligently, the results from simulated icing facilities can be of considerable value. There will still have to be a lot more experience in natural icing conditions to ensure that all the conditions in which tests should be made are known and agreed. Until the artificial clouds have been developed to be a perfect simulation of all natural clouds it will always be necessary to check the findings of some tests in natural icing conditions. As the simulation techniques are improved, a greater proportion of the work can be done artificially and as more comparisons between results obtained in a natural icing cloud can be made with those obtained in artificial conditions, more confidence can be built up. I expect it will be many years before tests in the real thing will no longer be required but when only two or three parameters have to be controlled artificially it seems reasonable to forecast that despite the complexity of the problems involved, more and more solutions will be made available by means of artificial testing.

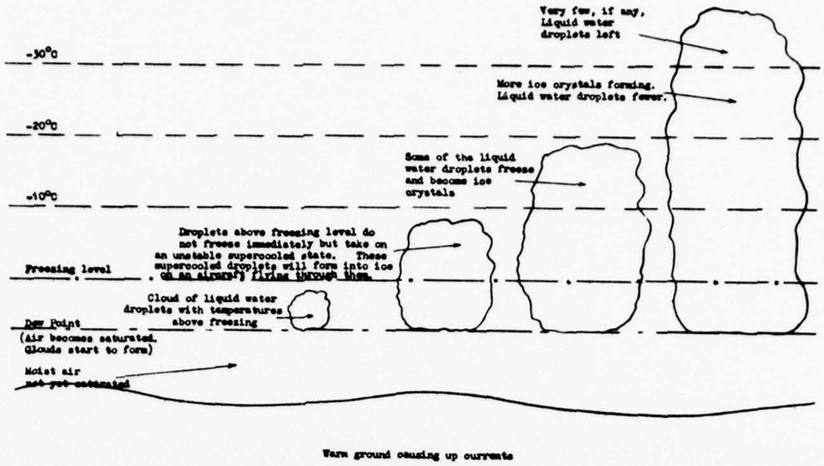


FIG. 1. GROWTH OF A CUMULUS CLOUD.

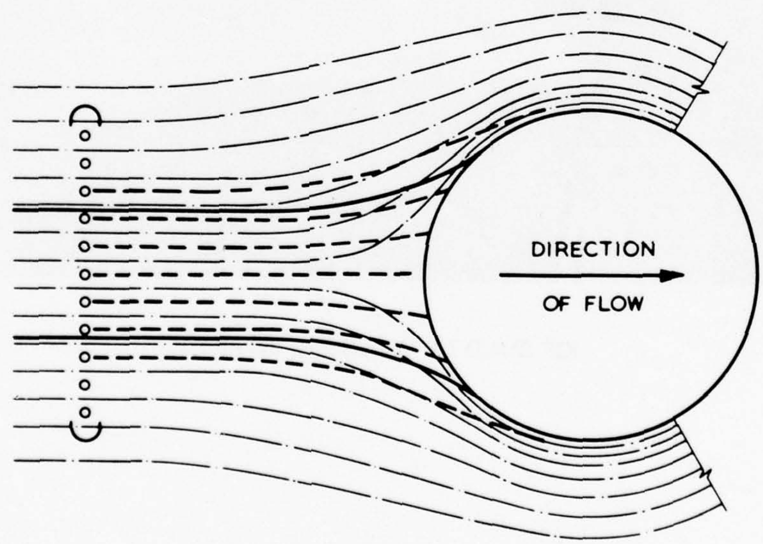


FIG. 2. IMPINGEMENT OF WATER DROPLETS ON A CYLINDER.

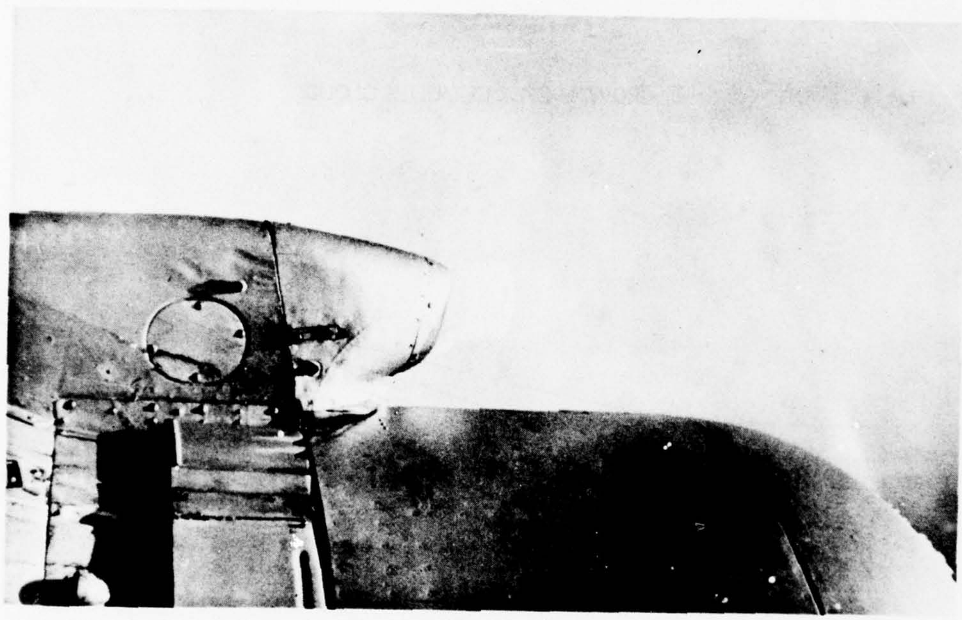
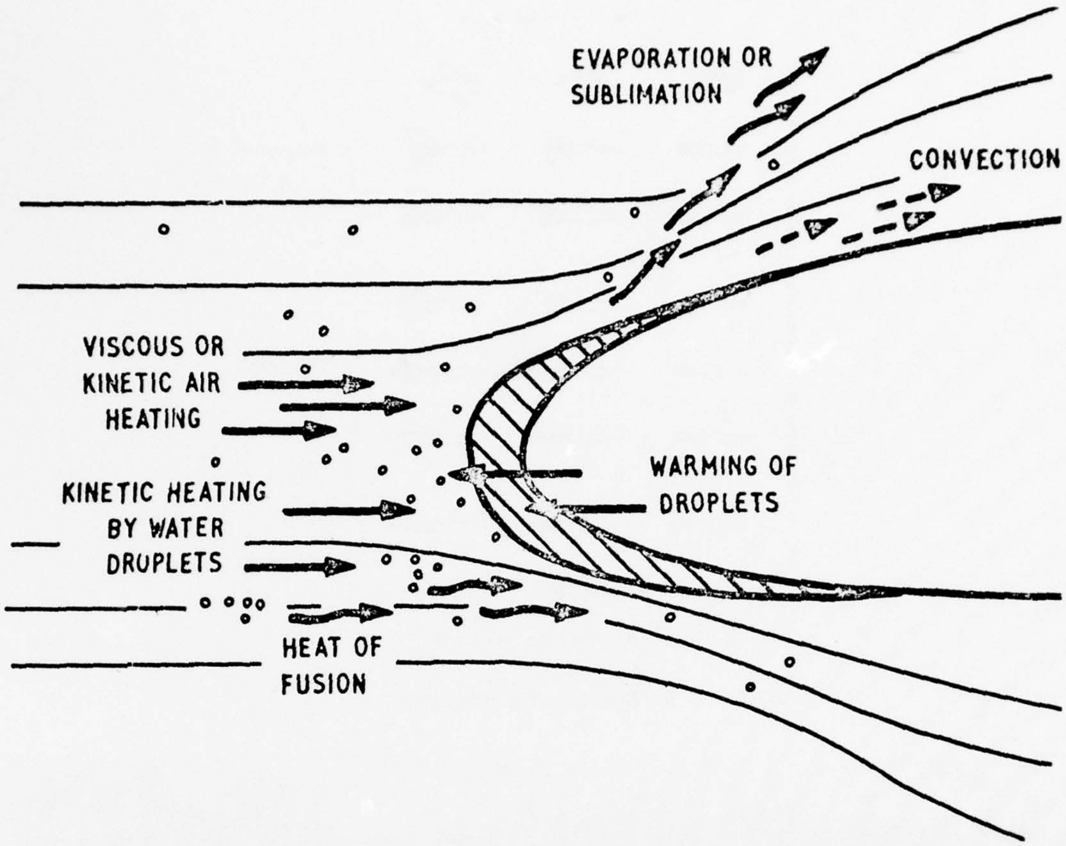


FIG. 3. ICE BUILD UP ON ENGINE INTAKE.



$$Q_f + Q_k + Q_i + Q_v - Q_w - Q_c - Q_e = Q_s \qquad (1)$$

WHERE

Q_f = HEAT OF FUSION OF IMPINGING WATER

Q_k = KINETIC HEATING OF WATER DROPLETS

Q_i = ICE COOLING (FROM 0 °C. TO θ_s)

Q_v = KINETIC HEATING FROM AIR

Q_w = WATER HEATING FROM θ_o TO 0 °C.

Q_c CONVECTIVE HEAT LOSS

Q_e EVAPORATIVE HEAT LOSS

Q_s CONDUCTIVE HEAT LOSS FROM SURFACE

θ_o AMBIENT AIR TEMPERATURE (°C.)

θ_s ICING SURFACE TEMPERATURE

FIG.4. THE HEAT FLOW EQUATION FOR THE ICING SURFACE ON AN UNHEATED BODY

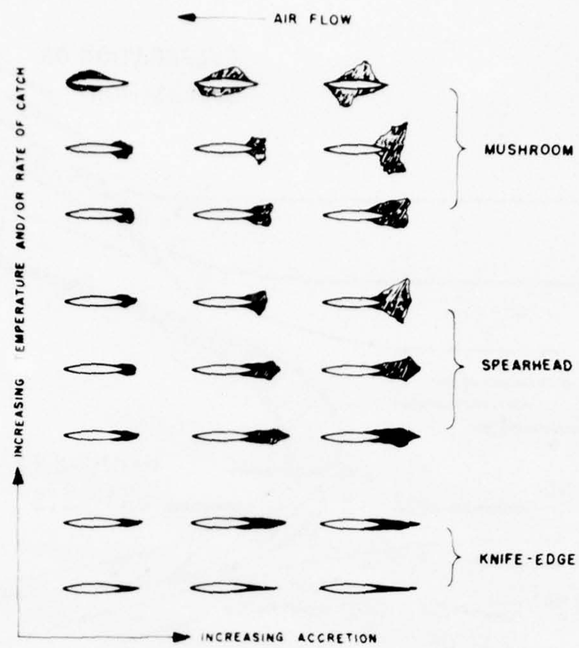


FIG. 5. ICE SHAPES ON A THIN STRUT.

Figure 6. A&AEE Blower Tunnel Icing Facility.

DEVELOPMENT OF THE CH-47 FOR FLIGHT IN ICING CONDITIONS

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INTRODUCTION

With the increasing use of the helicopter by the military in recent years, worldwide deployment and operation of this aircraft have emphasized the need for serious evaluation of the impact of the icing environment on its capabilities. The requirement for ice-protection systems on various helicopter components such as engine inlets, rotors, windshields, and so forth must be established for the full range of helicopter sizes and configurations. As a vital portion of the investigation of ice-protection systems, rotor blade deicing must be evaluated to determine whether a deicing system is essential for a helicopter operating in an icing environment. Rotor deicing and anti-icing systems are generally the most expensive of the ice-protection devices. It is therefore necessary to examine the effect of rotor blade ice accretions on the operational capability of helicopters.

The CH-47 Chinook helicopter (Figure 1), manufactured by the Boeing Vertol Company, is a twin-engine, tandem-rotor aircraft with a maximum gross weight of 50,000 pounds. The aircraft is powered by the Lycoming T55-L-series of engines. This helicopter is designed for the transport of cargo, troops, and weapons in any weather at any time of the day or night. The design, development, and use of this helicopter have been directed toward this capability.

The CH-47A was flight-tested in icing conditions behind a USAF C-130 tanker aircraft equipped with an icing spray rig during the winters of 1963-64 and 1964-65. The CH-47 does not have a rotor blade deicing system; however, the helicopter was able to fly for extended periods of time with large accumulations of ice on the blades.

CH-47 TESTS UNDER ICING CONDITIONS

Early in the CH-47 program chemical blade anti-icing was developed and tested. Two rows of holes were

Figure 1. Boeing Vertol CH-47 Chinook Helicopter

drilled in the leading edge of the blade which were fed by tubes routed from a distribution ring in the rotor attached to the rotor hub. This system was tested for flow pattern on the whirl tower at Wright-Patterson Air Force Base and was developed to the point where the distribution of anti-icing fluid at various rotor speeds and angles of attack was good enough to permit a trial under icing conditions. Unfortunately the spray rig available in the Eglin Air Force Base climatic hangar, where the testing was conducted, was not able to simulate adequate supercooled-water conditions and the tests were inconclusive (Figure 2). The problems of distribution and weight of the anti-icing fluid, restrictions on the length of time available for anti-icing, the effect of the holes in the blade on fatigue strength, and the cost of the system all led to the abandonment of this approach.

CH-47 FLIGHT TESTS IN ICING CLOUDS

After extensive all-weather climatic hangar and arctic tests, a CH-47A helicopter was flight-tested in an icing cloud produced by a spray system installed in a

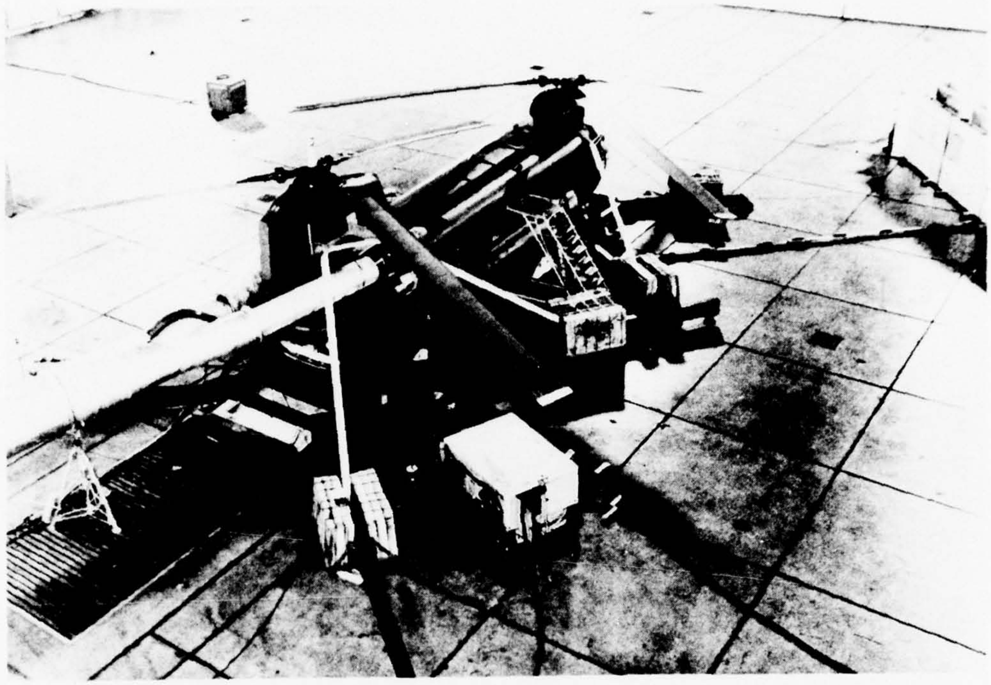


Figure 2. CH-47 Helicopter in the Climatic Hangar at Eglin Air Force Base

USAF C-130 aircraft at Wright-Patterson Air Force Base, Dayton, Ohio (Figure 3). During the tests in February 1965, the CH-47A made two flights of approximately 30 minutes each with the ambient temperature between +5 and -4°F. In these flights in the 16-foot-diameter icing cloud, the helicopter accumulated up to 1-1/2 inches of ice on the forward rotor blades and 1/2 to 3/4 inch on the aft blades (Figures 4 and 5). Asymmetric self-shedding of the rotor ice was observed and no attempt was made to induce complete shedding by changes in collective or cyclic pitch or by changes in rotor rpm. The helicopter was flown out of the icing cloud when the vibration became uncomfortable for the pilot. There were no problems with controllability or flying qualities in spite of the large amounts of ice accumulated. As a result of these icing tests, the CH-47 was cleared for flight into light icing without a requirement for blade deicing equipment. U.S. Air Force representatives indicated that the aircraft was satisfactory for flight in moderate icing conditions as a result of the tanker tests, but were unable to locate natural icing conditions of sufficient severity

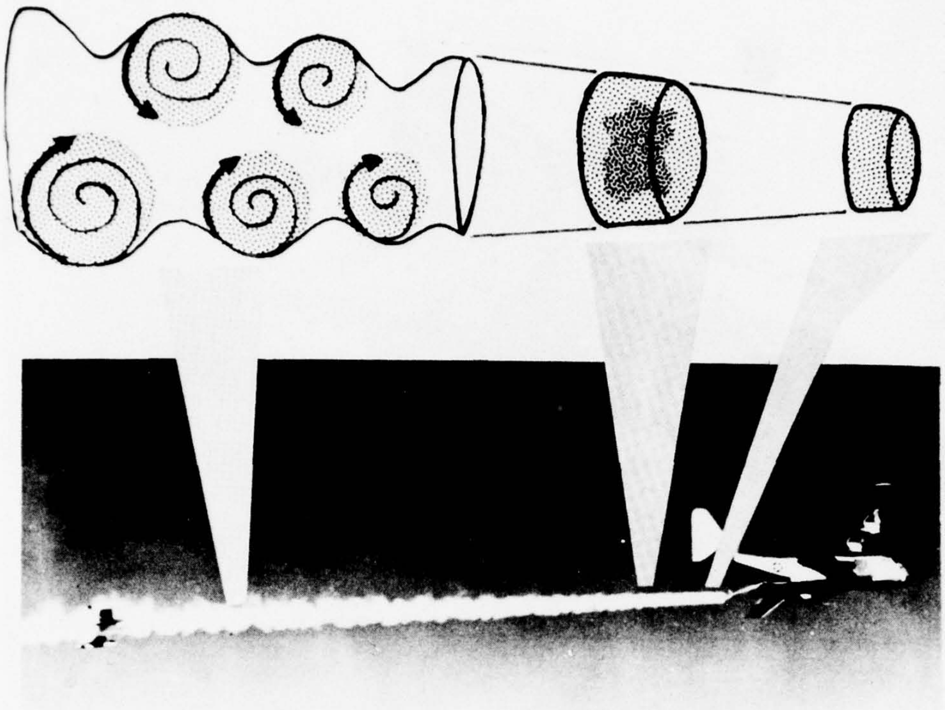


Figure 3. USAF C-130 Icing Tanker and Diagram of Spray Cloud Pattern

during the test period to verify the clearance.

Several features of the basic arrangement of the CH-47 enable the helicopter to perform in an icing environment. First, the critical systems are heated to prevent the accumulation of ice in those areas; windshield anti-icing, pitot, SAS ports, and heated engine inlets are provided. Secondly, the location of the engine inlets away from the fuselage prevents ice from being swept along the fuselage and into the engine intakes. The rotor blade sections are relatively large with strong, large-radius leading edges, minimizing possible impact damage to the blades from ice thrown from the blades and airframe. Pieces of ice more than 1-1/2 inches thick have been thrown from the CH-47A rotors in flight without damage to the blades or other parts of the helicopter. The CH-47A symmetrical-section rotor-blade boxes have 4-ply fiberglass skins and aluminum-

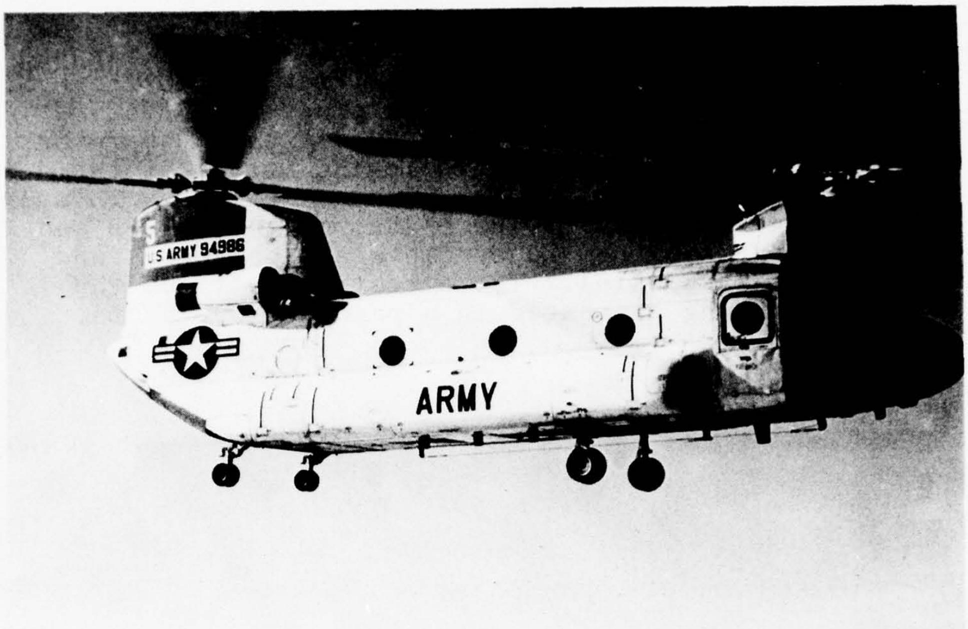
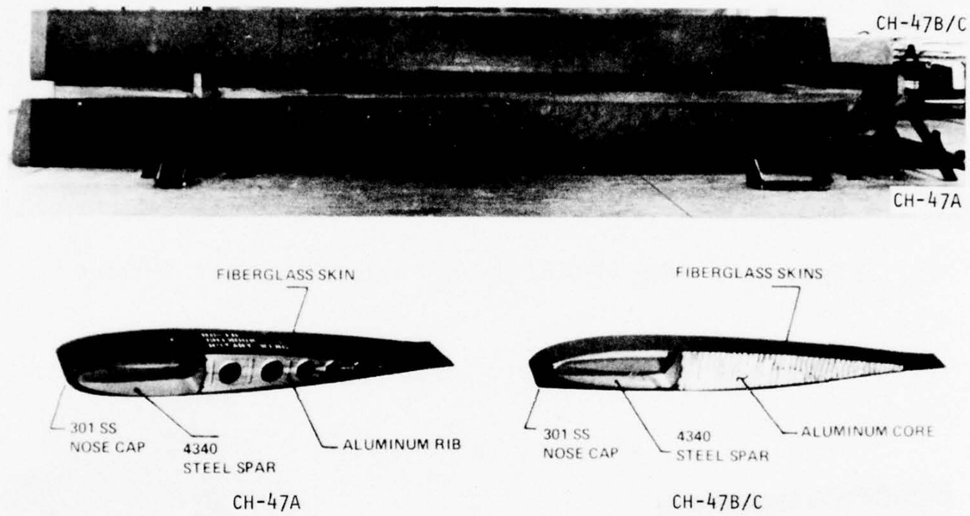


Figure 4. CH-47A With Ice on the Rotor Blades

Figure 5. Ice Accumulation on Forward Rotor Blade

rib construction and appear to be tolerant of ice (Figure 6). However, as this paper was being prepared new testing of a CH-47C aircraft flying behind the U.S. Army's CH-47C icing tanker was in progress. Preliminary results indicate that the CH-47C cambered rotor blades suffered multiple dents in the bottom of the rotor blades in the blade box area while flying in moderate icing conditions. The blades on the CH-47B and C models have aluminum honeycomb blade box cores and 3-ply fiberglass skins. These test results on the CH-47C are being presented in a paper by our hosts.



WALL THICKNESS COMPARISON		
	STA 67	STA 200
A	.140	.065
B/C	.176	.072

Figure 6. Comparison of Blade Construction for CH-47A and CH-47B/C

PROBLEMS ASSOCIATED WITH ROTOR ICE ACCRETION AND SHEDDING

Rotor ice accretion increases the power required by changes in the lift capability and increased drag. In the CH-47 icing tests, the rotor ice buildup did not cause an unsatisfactory loss of flight capability

because the aircraft had sufficient power margin available. Rotor ice accretion and asymmetric shedding did cause uncomfortable vibration levels in the helicopter; however, the helicopter was able to continue flight without danger of structural damage from the vibration. A problem created by rotor ice shedding is potential engine damage from ingestion of ice. Ice might strike the engine directly or might cause fuselage ice to be deflected and ingested, with a resultant loss of engine power due to flameout or compressor damage.

Engine transonic compressor blades are also apparently more vulnerable on the CH-47C model than the subsonic compressor blades used in earlier engines, since the engines were also damaged in the same test flight mentioned above. Field experience has recently reinforced the need for an all-weather engine inlet screen. The current standard CH-47 engine inlet screen does not have alternate air provisions and, of course, is not anti-iced, so that it must be removed at temperatures below 40°F. Ice and other foreign objects may then enter the engine when the aircraft is operated without the screen. A new bypass screen has been under development to permit continuous use even in icing conditions, when direct impingement will result in a blocked screen in a very short time. The alternate air path is through an annulus at the rear of the screen (Figure 7). This screen is in the advanced-qualification status under an ECP, with planned incorporation in the fleet by next winter. Icing tunnel tests at the Lewis Research Center, Cleveland, Ohio, have been very satisfactory with this alternative airscreen.

PURPOSE OF ICING INVESTIGATION

A great deal of effort has gone into the development of rotor blade deicing systems by Boeing and other organizations because of the concern for the increased power required, vibration, and potential engine and airframe damage from rotor ice. Operational rotor blade deicing is installed on the Boeing CH-46 (USMC), KV-107 (Japan), and CH-113 (RCAF) helicopters. Rotor deicing allows control of the ice thickness on the blades thus reducing the engine power required, reducing vibration buildup during ice asymmetric shedding, and reducing the potential for damage to the rotor blades, fuselage, and engines. The rotor deicing system requires a bonded blade heating blanket, sliprings, electrical

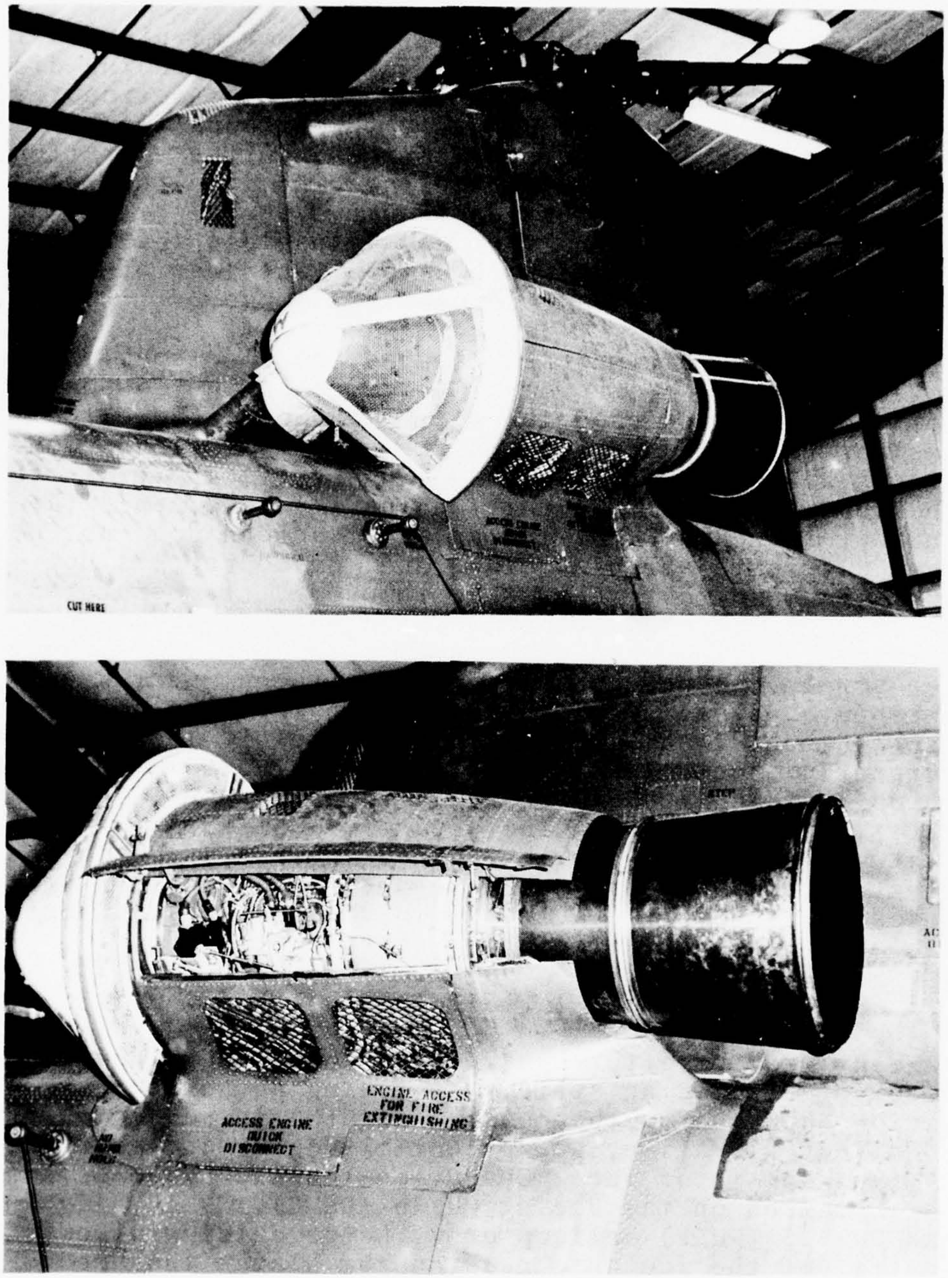


Figure 7. All-Weather Inlet Screen Under Development for the CH-47 Helicopter

wiring, stepping control system, and an ice detector with a timing control system (Figure 8).

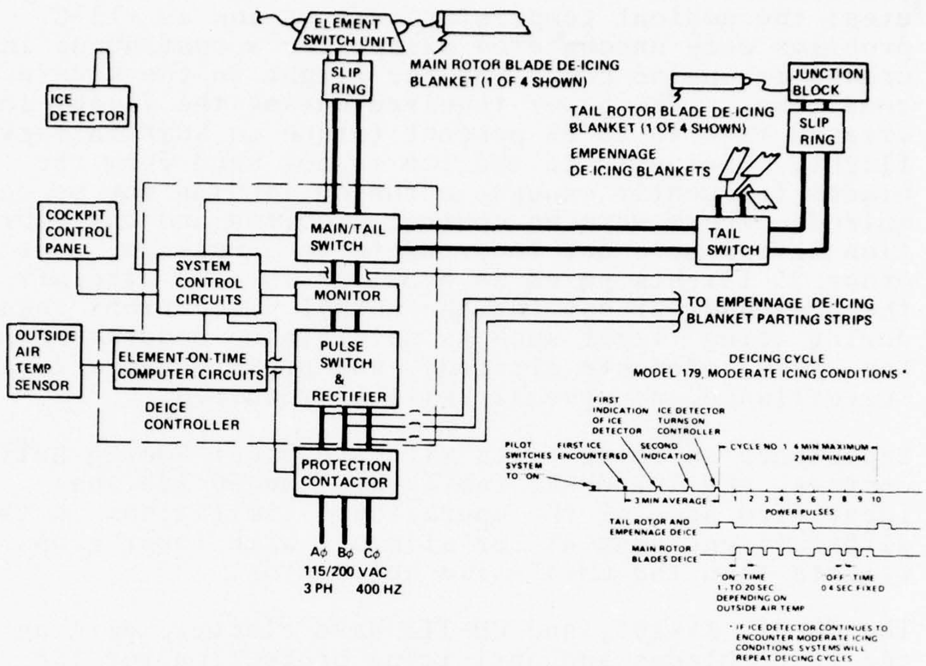


Figure 8. Typical Blade Electric Deicing System

The deicing system is exposed to severe operational environmental conditions such as rain, sand, and dust which dictate the use of erosion-protection materials to prevent possible damage to the heater blanket. Because the rotor airfoil contour must be closely maintained, it is difficult to provide a deicing heater blanket as an add-on kit for use only in cold weather. The principal disadvantage of a blade deicing system is that during most of the operational life of the helicopter it provides no capability but does require periodic maintenance.

SERVICE EXPERIENCE

In the years since operational use of the CH-47 began, many icing encounters have occurred. Some of the most notable were intentional flights by CH-47A helicopters

into predicted icing conditions in West Germany during the winter of 1971-72. Of 85 planned flights, 26 encountered significant accumulations of ice up to severe conditions. The flight in severe icing lasted 40 minutes; the ambient temperature was as low as -13°C. No problems were encountered except for a continuous increase in engine power for the flight in the severe conditions. The power required during the flight increased from 40 to 65 percent torque to sustain forward flight. Obviously if the ice is not shed from the blades frequently enough, a run-on landing may be required. There were no control problems and the vibration levels were not reported to be excessive. The other 25 flights posed no problems for the aircraft or the crew and, except for the normal precautions required during icing flight such as maintaining moderate cruising speed, adequate altitude, and proper navigational surveillance, no special skill is required.

Experience in icing tests with two other Boeing helicopters, the 107/CH-46 family and the BO 105, has identified some of the operational limitations in this difficult environment for aircraft with lower gross weights than the CH-47-size helicopter.

The CH-46, KV-107, and CH-113 have electric deicing of the rotor blades and anti-icing protection for the other critical areas of windshield, airspeed system, SAS ports, and engine inlets. This 28-watt-per-square-inch, sequencing, electric deicing system has been incorporated in all CH-46 rotor blades. Tests have been conducted at the National Research Council icing spray rig at Uplands Airport, Ottawa, Canada, and have demonstrated the ability to prevent the accumulation of significant rotor blade ice on the leading edges in any icing conditions throughout the temperature range where natural icing can occur. This system was originally developed for the Canadian Air Force CH-113 and in the past 8 years has operated successfully in actual icing conditions. The same system is also used by the Japanese Air Force on their KV-107 aircraft. The U.S. Navy and U.S. Marines have rarely used the deicing systems and have deactivated them to eliminate the maintenance costs associated with such complex systems. A CH-46 has been operated at Uplands with the deicing system off while in the icing cloud for extended periods. Large quantities of ice accrete quickly and large

increases in power occur so rapidly that extended flight in natural icing conditions at low temperatures would be difficult without deicing on an aircraft of this size.

Tests in the icing tower have shown that the BO 105 can run out of power available in as little as 2 minutes in moderate icing conditions at low temperature (Figure 9). Therefore we see a trend that the smaller helicopters are unable to continue flight in icing conditions because of the apparent size effect of the blade section, catch efficiency, drag characteristics of the accumulated ice, and amount of excess power available. It is our observation that the CH-46-size helicopter (23,000 pounds gross weight) may be marginal in its ability to cope with flight in continuous moderate icing conditions at low temperature without a deicing system for reasons of geometry, drag, and the disproportionate increase in power required due to blade icing. However, further work can be done to explore the possibility of shedding ice by pilot action in the critical temperatures below the self-shedding range of about -8°C.

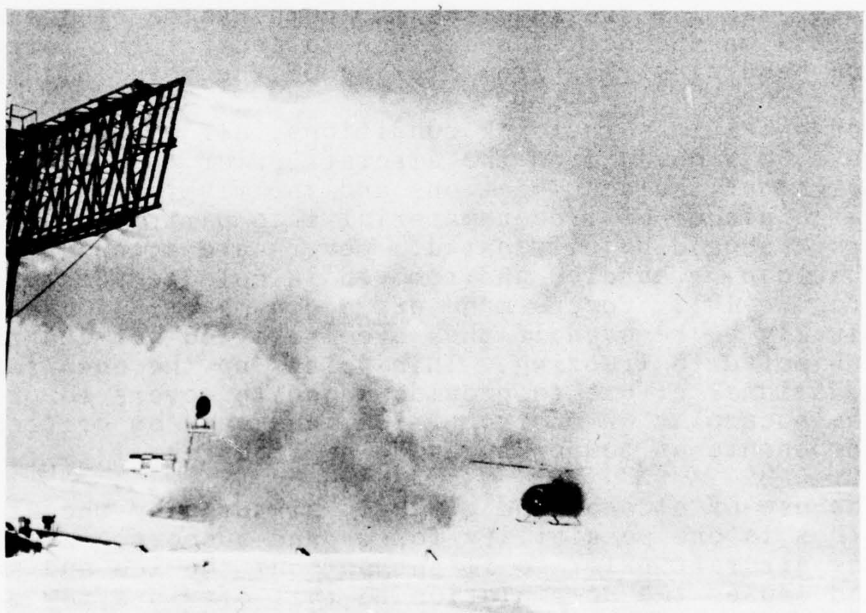


Figure 9. BO 105 Helicopter in the Icing Spray Rig at Uplands, Ottawa, Canada

In aircraft the size of the Chinook, 10 to 20 minutes of flight in moderate icing at low temperature can be tolerated due to available engine power and the vibration level buildup, even with asymmetrical shedding of ice; this allows the pilot sufficient time to take action to cause the ice to shed. Successful shedding methods such as dropping the collective-pitch lever and then immediately returning it to the original position, or by a 10-percent sweep of rotor rpm, have been effective on other medium-lift helicopters (MLH). The collective dump is obviously not very satisfactory to the crew flying on instruments, but the rpm sweep has proven to be an acceptable method. Attempts have been made by CH-47 pilots to shed ice by means of the rpm sweep in the current icing tanker tests which are described in the aforementioned paper. It is clear from other testing that even rapid movement of the cyclic-pitch lever will not cause the ice to shed.

Blade bending must occur to initiate the shearing of rigid, adherent ice. Furthermore, the mechanism of shedding ice from the rotor blades at lower temperatures, according to H.R. Stallabrass of the NRC, is intergranular and requires the combination of shear stress on the accreted ice due to centrifugal force and bending stress from flexing of the rotor blades.

For operations in icing conditions, all ice and snow must be removed from the aircraft prior to run-up. The weight of the accumulations and the risk of throwing large pieces of frozen material into parts of the aircraft should be eliminated. Covers are acceptable if they can be handled and removed in cold temperatures (Figure 10). Covers made of modern materials cannot usually be removed if they are installed wet and then subjected to freezing. This points up the need for additional effort to provide adequate covers to prevent the accumulation of frost, ice, and snow on critical components at temperatures below freezing.

The use of alcohol and glycerin mixtures by the airlines is one possibility for ground support. Washing the aircraft prior to flight softens the ice and snow and causes the accumulation to fall off in a few minutes; however, this requires large quantities of fluid and takes valuable time and sizable ground support equipment. Ground combustion heaters will remove the frozen material but their use is very time-consuming.

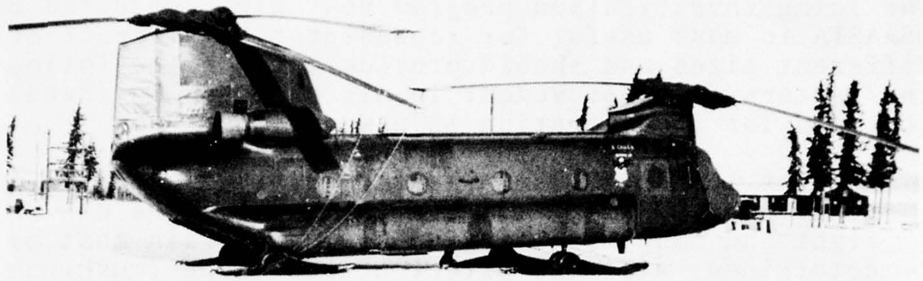


Figure 10. CH-47 Helicopter With Ice-Protection Covers

As for cockpit requirements, existing flight instruments and navigational aids in an aircraft such as the CH-47 are sufficient to permit flight under instrument meteorological conditions (IMC). However, as flight in icing conditions becomes an operational requirement, thereby increasing IFR operations, it is felt that this equipment should be supplemented by a radar altimeter, a precision position-navigation system, and an advanced flight-control system. These systems provide the desired increase in operational capability of the aircraft by reducing pilot workload, providing precise flight-path control, and increasing safety. A cockpit indication of ice accumulation or icing conditions would be useful to the pilot in providing additional information on which to base appropriate action.

The operating techniques have been discussed earlier and the major added effort is to initiate self-shedding of the rotor blades as soon as the vibration level is high enough to indicate that a sufficient mass of ice is accreted to permit self-shedding through pilot action.

RECOMMENDED ICING INVESTIGATION

The icing investigation program now being conducted by USAASTA is most useful for representative aircraft of different sizes and should provide data on the following factors for improvement in aircraft now in inventory and for incorporation in new designs:

- Rate of Ice Accretion--The rate of ice accretion on rotor blades during flights into conditions of light and moderate icing and freezing rain must be determined; also the effect of ice shape (mushroom/spear) on the helicopter performance, vibration, and self-shedding capability.

- Aircraft Damage From Vibration and Shed Ice--Vibration levels and aircraft damage due to asymmetric ice shedding and induced ice shedding must be determined. Aircraft potential damage from vibration and from ice impact on the rotor blades, fuselage, or engine should be examined. The ability to induce ice shedding by rotor rpm sweeps or by collective-pitch changes should be evaluated as operational procedures.

- Flight and Approach Procedures in Icing Conditions--Ice shedding during transition from hover and during landing must be studied; procedures should be established for flight and landing conditions when operating with accreted ice on the aircraft. The operational procedures for VFR and IFR icing flights would use the results of these tests. Rotor shutdown procedures during high winds after an icing encounter should also be evaluated.

- Protection of Engine Inlets--Engine inlets must be protected from shed ice, i.e., with bypass screens or deflectors. The ability of the bypass screens or deflectors to protect the engine from ice damage while providing adequate engine airflow and distortion level should be examined.

- Cruise Guide Indicator--A cruise guide indicator should be evaluated as a means of determining the rate of rotor ice buildup and the effect of asymmetrical ice shedding.

- Engine Dual Ignition--The engines should be equipped with dual ignition systems, with one system capable of continuous ignition during icing encounters.
- Ice Accretion Measurement--Ice detectors and icing-rate meters should be tested for incorporation as a means of evaluating the severity of icing.
- Power Measurement--Rotor torque and engine torque measurements should be taken to determine the power margin available during the icing tests of the rotor and engine inlet protection.

The overall objective of the icing investigations should be to determine the existing capability of helicopters to operate in an icing environment and to provide guideline criteria for establishing whether blade deicing is required on various sizes of helicopters. A primary purpose would be to examine the icing impact on the medium-lift-class helicopter. This icing examination would provide data that could be expanded to include heavy-lift and UTTAS-size helicopters.

CONCLUSIONS

It is our opinion that sustained safe flight in moderate icing conditions in MLH-size helicopters is operationally acceptable without rotor blade deicing. Engine inlet protection must be installed at all times. Superficial damage to the rotor blades may occur which will not affect safety of flight, but will possibly require maintenance for the rotor blades. Smaller helicopters probably cannot achieve self-shedding through pilot action, although larger aircraft up to 25,000 pounds gross weight should be tested without blade protection to determine possible techniques that are acceptable. The icing-tanker method is ideal for this feasibility investigation.

When mission requirements dictate repeated flights in conditions of continuous moderate icing, we must conclude from experience that the electric sequencing deicing system holds the most promise. The tradeoffs for consideration are the cost, weight, reliability, and maintainability of the new systems balanced against the occasional superficial blade damage and the associated maintenance costs for the larger helicopters.

BRITISH AIRWAYS HELICOPTERS EXPERIENCE IN CIVIL CERTIFICATION AND OPERATIONS IN ICING CONDITIONS

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Introduction

When British Airways Helicopters signed their contract for the first two Sikorsky S61 Helicopters in August 1963 the prime consideration was the introduction of a scheduled service to replace the fixed wing de Havilland Rapides on the Penzance - Scilly Isles service off the South west coast of England and to provide a helicopter service for the Oil Companies about to embark on oil exploration around the coasts of the United Kingdom.

Planning for the future British Airways Helicopters were of the opinion that whatever may transpire with regard to the introduction or otherwise of scheduled helicopter services, the oil companies were going to be busy with oil exploration work around the coast of Great Britain for at least 25 years. To establish a strong position for the company in the initial phases of this work in the North Sea the Board felt that it made sound economic sense to develop along these lines, with oil exploration support planned as a major activity for the foreseeable future.

The oil rig work would also have a direct bearing on any future requirement to operate scheduled helicopter services for conventional passenger traffic. The oil companies requirements of the helicopter service amount to, what is substantially a scheduled passenger and freight service to the North Sea rigs. It has to operate in all

weathers and represents quite closely the conditions that would apply to scheduled passenger operations.

The management of BAH realising the importance of developing operating procedures to meet these requirements, undertook a series of flight test programmes. This paper deals with that concerned with helicopter icing.

Early History

With the introduction of the S61N into service in 1964 BAH called for the manufacturers to obtain FAA and/or CAA approval for the aircraft to fly in icing conditions. The problem on the S61N was further complicated by ice build up on the cabin roof and the ingestion of breakaway ice by the engines resulting in damage.

The Sikorsky Company had already embarked on a series of tests and had developed an ingestion protection over the engine intakes which had been used by the U.S. Air Force and the Royal Canadian Navy, it was hoped if used in conjunction with Aerodynamic Discontinuity Profile (ADP) tape would give some icing protection. In the early part of 1966 Sikorsky presented to the FAA a proposal for the evaluation and approval of a certain configuration of the S61N for operation in known icing conditions. This configuration consisted of a standard S61N equipped for ADP tape on the blades, the engine air inlet ice deflector and heated windshields, engine intakes and pitot static tubes. Since it was the first proposal of its type, the FAA gave it lengthy consideration. It has long been recognized that the helicopter could not enjoy the use of the icing substantiation techniques developed for demonstrating these capabilities for fixed wing aircraft. It is, at this stage in the development of icing tunnels, necessary for the helicopter to demonstrate its capabilities in natural icing conditions in the atmosphere.

Evaluation of Engine Ice Deflector

In 1967 after discussions had taken place between the FAA, Sikorsky, CAA and BAH it appeared that the FAA were unlikely to approve the S61N for flight in icing conditions on the evidence of the tests carried out to that date. In as much as the full spectrum of icing conditions for which the FAA required demonstration cannot be produced upon demand in the atmosphere, and since the FAA had, up to this point, refused to consider any sort of partial icing approvals, BAH considered the S61N had been given a rather severe handicap in demonstrating its ability to operate under such conditions.

The CAA agreed to accept Sikorsky's evidence providing some actual tests were carried out in the U.K., and issued a draft change sheet to the Flight Manual which allowed the S61N to be flown on oil rig operations, with the ice shield, subject to take off weight reductions. Flight in icing conditions, to test the effectiveness of tape and shields, was allowed for special tests under 'B' flight conditions. In being able to carry out this work for themselves, the company have distinct advantage of having their own design approval organisation, which is of course, quite apart from the regular maintenance staff.

The evaluation of the engine shields and ADP tape was carried out during the 1967/68 winter, although this was a cautious investigation the pilots were happier at having some form of ice protection for inadvertant flight in ice and a certain amount of experience was gained.

Icing Programme 1968-70

In 1968 with the known requirement at that time for the Royal Navy to operate in icing conditions and the knowledge that A & AEE Boscombe Down were embarking on an icing programme for military helicopters it seemed

adequate justification for BAH to request assistance from the then Ministry of Technology.

A preliminary discussion was held in the autumn of 1968 and it was agreed that if BAH provided a suitably instrumented S61N with crew and observers the Ministry would support the work within certain limitations. Long delivery dates for specialised equipment and aircraft availability prevented the work commencing during the winter 1968/69. Sikorsky Aircraft showed considerable interest in the proposed trials and a Sikorsky Engineer participated in the flight programme which was conducted during the winter 1969/70 in the main from the BAH base at Aberdeen Scotland.

The aircraft was installed with standard winterisation equipment including the Engine Air Inlet Ice Deflector and instrumented to record parameters such as engine torques, rotor RPM, airspeed, altitude, vertical, fore and aft, and lateral vibration, control positions, OAT and icing severity on a recording oscillograph.

The ice encounters were in icing clouds of strato cumulus (patches not layer) and cumulus form. This necessitated changing directional control settings to remain in the cloud for ice accretion, making it difficult to measure performance degradation. During the flights helicopter performance and control characteristics were not by observation, noticeably affected.

There were 36 icing search flights and ice was encountered in 17.Out of a total of 38 hours 15 mins flying time logged, 16 hours 19 mins were in icing conditions. The results obtained were remarkable in a negative way, in that the effect of up to one inch of airframe ice was far less marked than anticipated. This was encouraging and with the high degree of confidence obtained another winters work was planned.

1970/71 A successful winter

The 1970/71 trials were a continuation of the work carried out previously. It is weel known that icing is not continuous within a cloud and icing encounters in a single cloud may be seperated by periods of light to severe icing of varying lengths. For greater manoeuveability and to avoid interference from/to other air traffic, the flying was conducted mainly at the weekends in an area over the sea to the east of Aberdeen.

Weather Conditions

Most of the flying was made in stratiform type cloud associated with frontal depression type conditions. This made it possible to measure performance degradation because greater horizontal coverage permitted operation in straight and level flight.

Heights varied from the surface to 7,000ft and temperatures from 0°C down to -12°C. Icing conditions encountered varied from light to severe glazed and/or rime ice some moderate snow and heavy sleet/rain at temperatures just below 0°C.

Flight Information

The 1970/71 trials consisted of 18 flights, 27 hours were flown in actual icing conditions out of a total of 30 hours 20 minutes. On flights 1 to 9 the aircraft was loaded to approximately 17,500lbs and flights 10 to 18 the T.O.W. was approaching the maimum of 19,000lbs.

During the flights various performance parameters were recorded to assess the effect of ice accretion on

the airframe and the rotor blades, with particular attention to 70 Kts (minimum power speed) and at the high speed end 110 Kts.

The aim was to maintain the aircraft in icing conditions for as long as possible, the following procedure was adopted.

a. After take off and before entering icing conditions, a performance run was made to establish a reference whilst the aircraft was clear of ice.

b. When the conditions were right and a reasonable amount of ice had been accreted, the aircraft was returned to reference height and the controls set to give straight and level flight and a five minute run was recorded.

Between the performance runs the pilot, whilst still remaining in icing conditions, was able to explore the flight envelope and assess the handling characteristics of the aircraft.

General Observations

On entering icing conditions the build up of ice began almost immediately, the speed of build up depending on the conditions and temperature. Heavy deposits of ice were experienced during most flights up to a maximum of $2\frac{1}{2}$ inches and during some flights complete shedding was made by reducing altitude below the freezing level and second deposits were then build up.

From the cockpit, ice was always observed in the same places. Mainly on the ice detector, the centre windscreen, windsceen wipers, OAT probe, front of floats, window handles, and by use of a mirror the pitot mast

and front of the engine inlet ice deflector. It was observed in temperatures around -3° to $-5^{\circ}C$ that ice on the windscreen wipers in contact with the heated windscreen melts, runs back over the top and sides of the cockpit in thin streams and then freezes. It is thought that it is these small deposits, which, when ice is shedding, fly back into the engine and may well have been the cause of engine damage experienced in the past.

At the end of most icing sorties an instrument approach was made maintaining altitude above the FL and then a rapid descent and landing made so that ice could be observed and photographed. Generally some ice was shed during this phase, but deposits were obvious in the areas already indicated, with other deposits on the undercarriage support struts, associated pipes and cable looms, along the mooring rope and its attachments, on the tail oleo, the tail wheel, the leading edge of the stabilizer and on the front surface of the nose.

There was no evidence of damage to rotors and airframe due to shed ice throughout the trial. The accretion of ice on the airframe did not present any problem.

Rotor Blade Icing

Although it is difficult to know how often main rotor blade icing may have occured it appears from the magnitude of the excess power that some degree of rotor blade icing may have occured during all of the flights recorded at speeds close to 110 Kts., even including flight in ambient temperatures as high as $-2^{\circ}C$, or else these amounts of power represent large increases in weight and drag due to airframe icing.

On landing after each flight the main and tail rotors were found clean down to the root ends, but substantial deposits were always obvious on pitch change rods, droop

stops, dampers and bifilar weights.

Engines/Intake

The engine inlet ice guards and the anti-icing system were found satisfactory for operating in the icing environments encountered no engine or intake damage being sustained.

Effect of Accretion on CG

To establish this problem, an assessment was made in which the AFCS pitch was carefully nulled in straight and level flight with the altitude indicator showing level horizon, at a speed of 110 Kts. After approximately one hour in varying icing conditions and 2 inches of ice accretion the null indicator was showing two-thirds of Full Scale Deflection to the left. The altitude indicator by this time showing $2\frac{1}{2}$ degrees nose down. The pitch beeper had been used to maintain altitude, resulting, with a fixed collective position, in a reduction of speed to 105 Kts. Any subsequent slight turbulence or cyclic control movements or beeping caused the pitch authority of AFCS to be exceeded. This was not considered to be in any way hazardous but calls for careful loading of the aircraft and frequent trimming to maintain maximum efficiency of the AFCS.

Performance

The most significant fact emerging from the trials was difference in extra power required between flight speeds of approximately 70 Kts and 110 Kts.

At 70 Kts a maximum 10% increase in power was required with approximately one inch of ice on the airframe and OAT of -8.5°C whereas at 105 Kts a maximum of 60% increase in power was measured with approximately on inch on the airframe and OAT of -7.5°C.

These tests gave indications that a reduction of forward speed assisted the process of ice shedding. Ice adhered at normal cruising speeds even at relatively high temperatures (-2°C) to a greater extent than a minimum speed of 70 Kts, in fact, at 70 Kts, one case occured showing no power increase in light icing for a period of 1½ hours in temperatures between -6°C and -7°C.

The work continued during the winters of 1971/72 and 1972/73. During 1971/72 out of 17 hours total flying; 9 hours were in icing conditions and in 1972/73 out of 13 hours 45 minutes, 9 hours 30 minutes were in icing conditions. The conditions encountered were similar to those already reported.

To date British Airways Helicopters have flown 123 hours on their icing programme, 88 hours in icing conditions and have demonstrated to the Airworthiness Division of the Civil Aviation Authority that it should be possible to maintain the airworthiness standards of the S61N helicopter at an acceptable level during flight in ice forming conditions and have on this basis been given approval to fly the aircraft in forecast light icing conditions. BAH are already planning a programme for the 1974/75 winter. This together with the reporting of data from routine S61N flights, which encounter natural icing conditions should increase substantially the amount of information available on the subject of civil helicopter flight in icing conditions.

Acknowledgements

I must take this opportunity to thank the U.S. Army Aviation Systems Command for the opportunity of being able to present this paper and thank the British Airways Helicopter management for permission. And you, gentlemen for listening.

APPENDIX Photographs

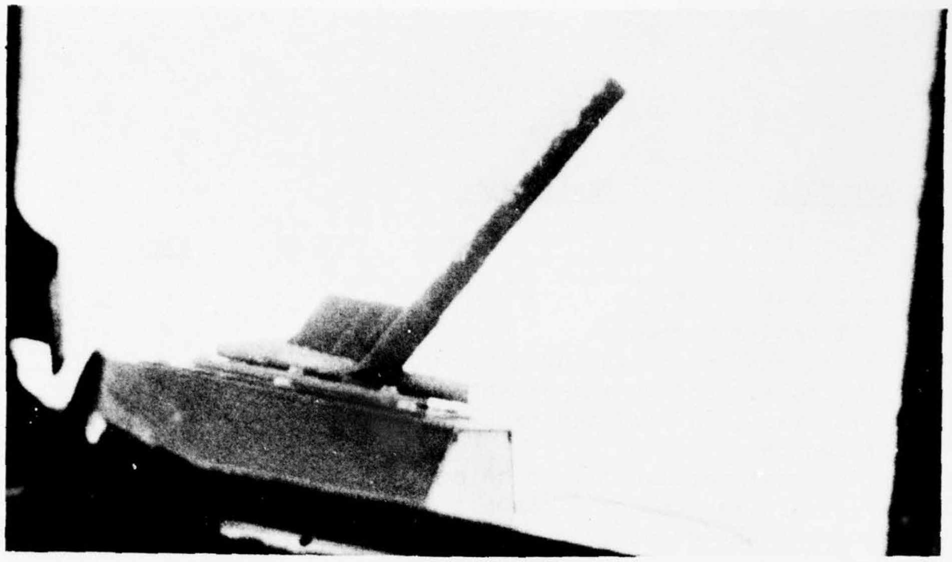

Fig.1.

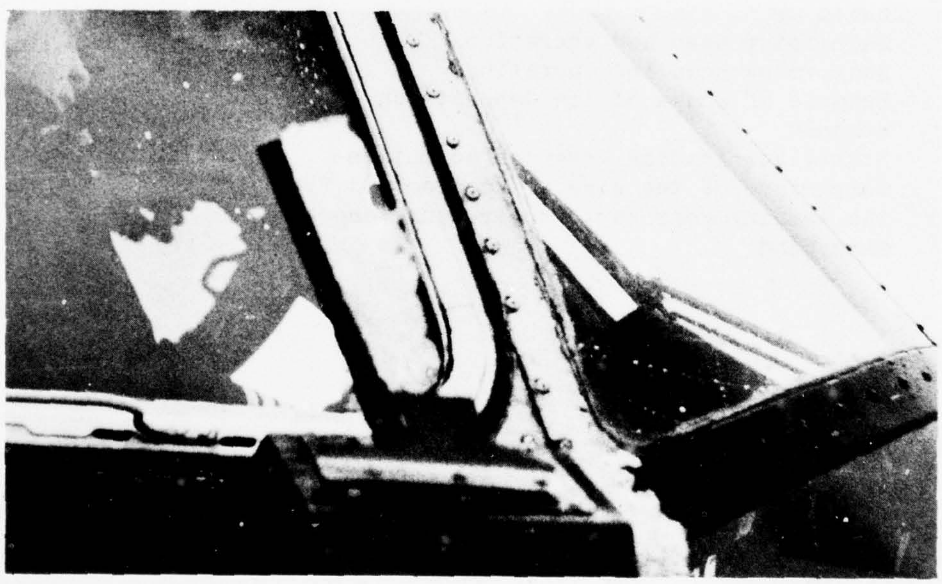

Fig.2.

AD-A061 422 ARMY AVIATION ENGINEERING FLIGHT ACTIVITY EDWARDS AF--ETC F/G 1/3
ROTARY WING ICING SYMPOSIUM. SUMMARY REPORT. VOLUME II.(U)
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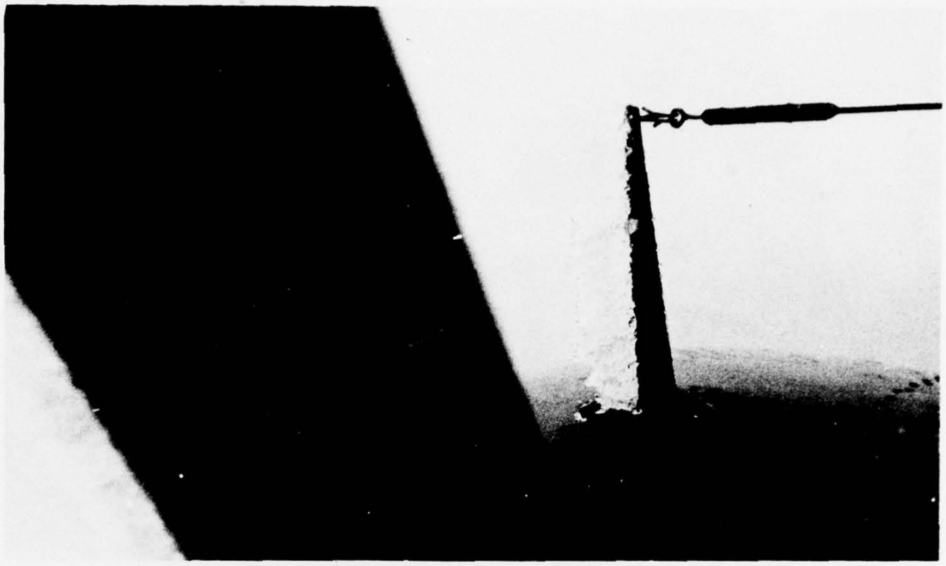

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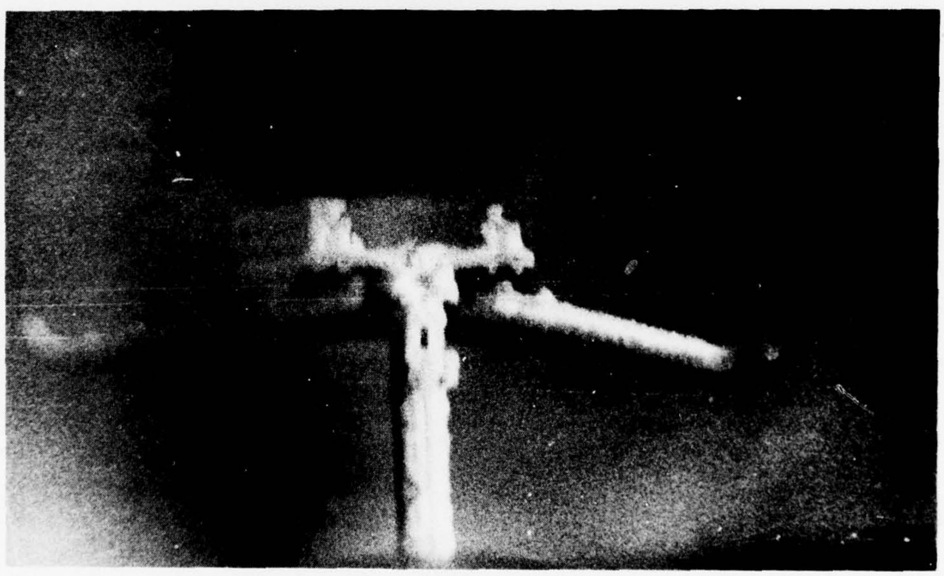

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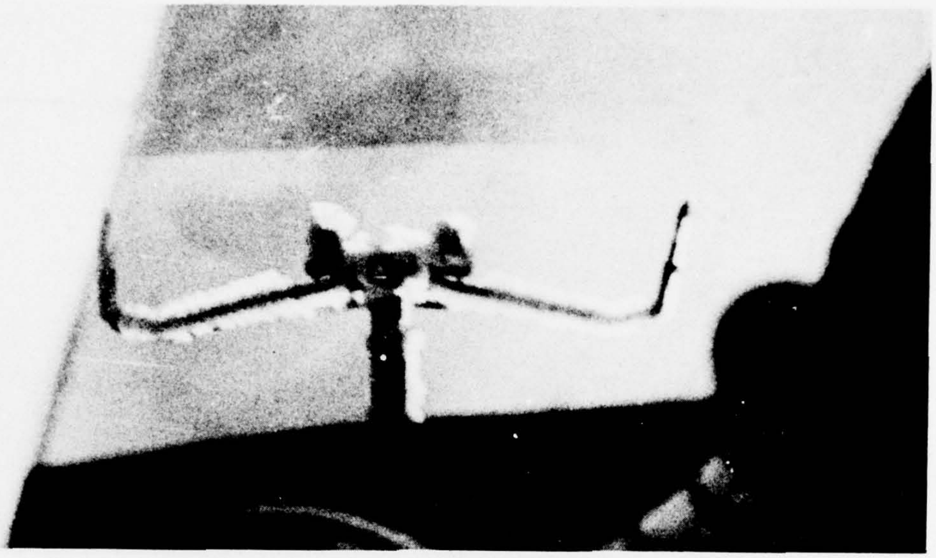
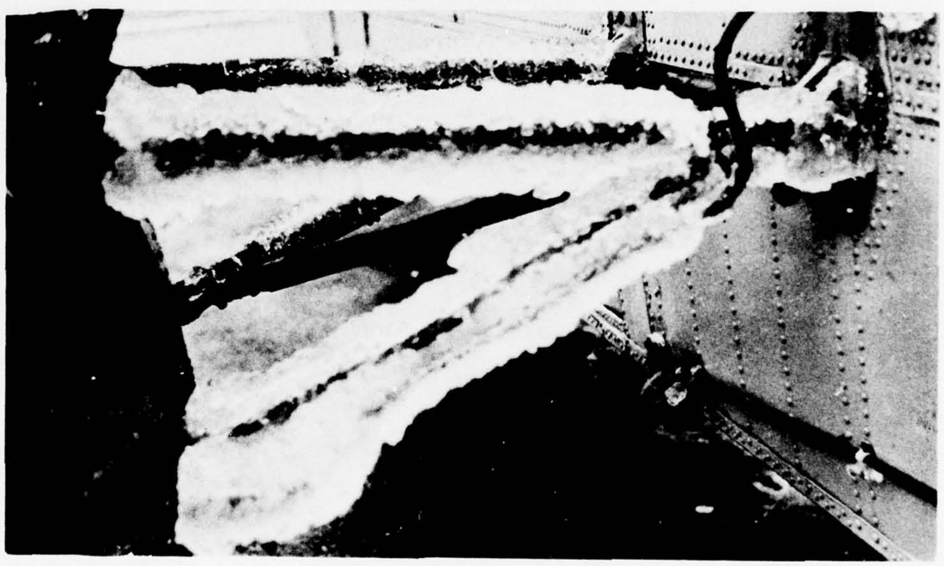


Fig.5.



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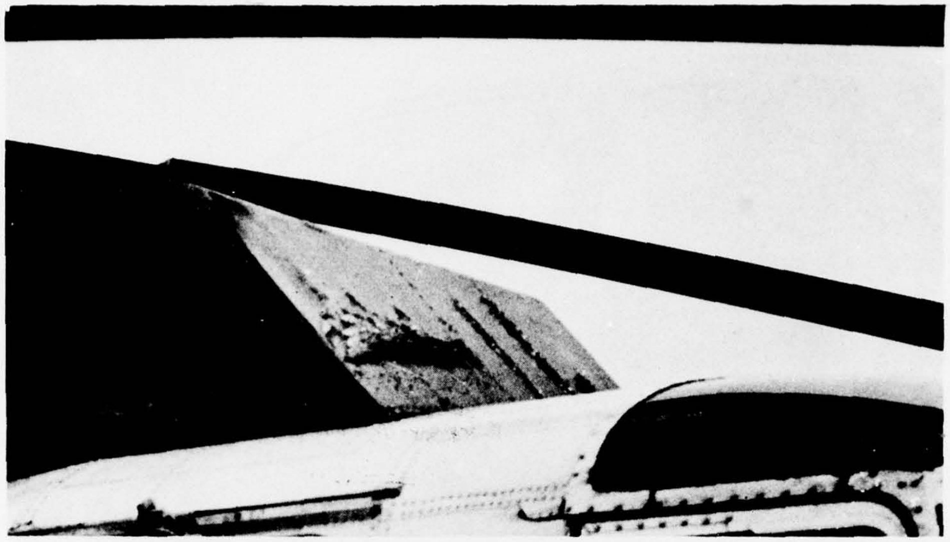

Fig.7.

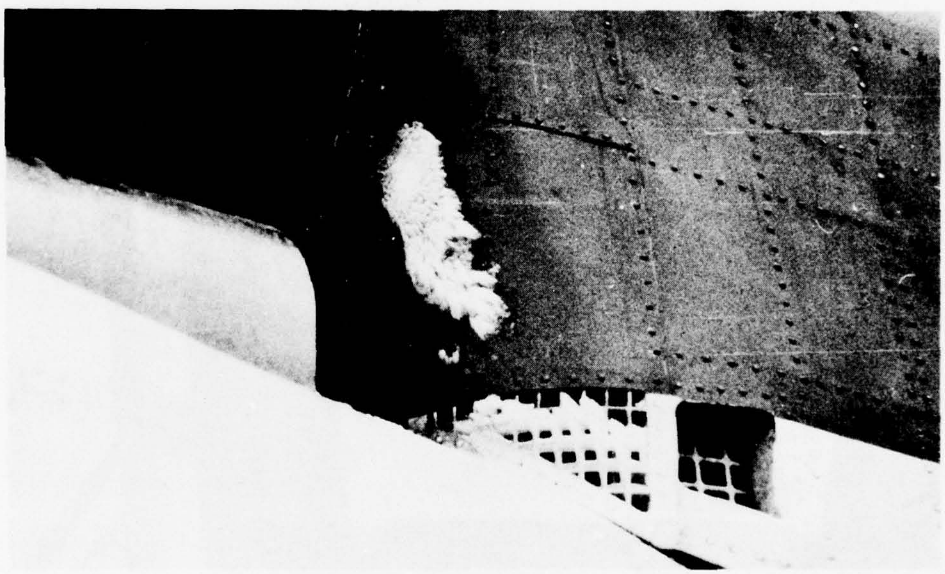

Fig.8.

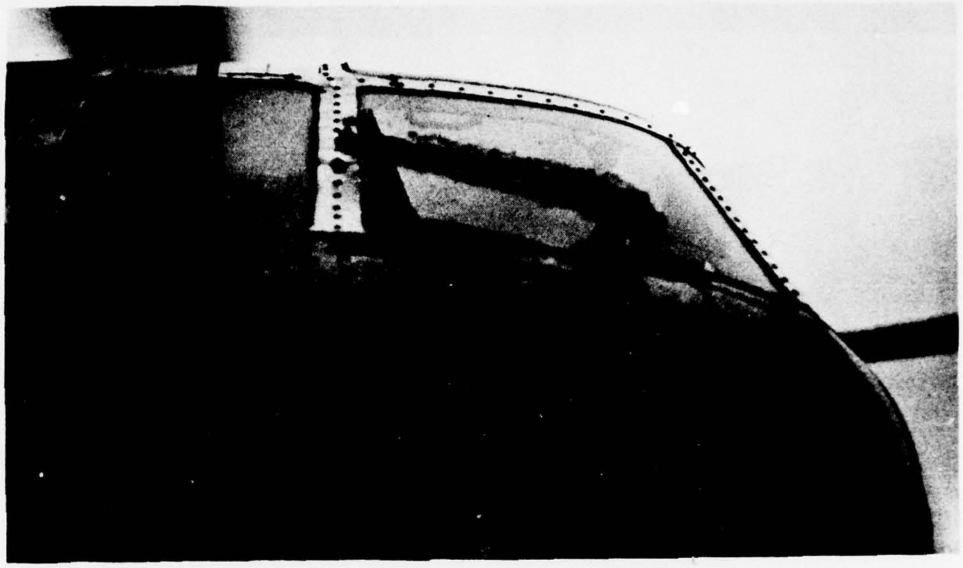

Fig.9.

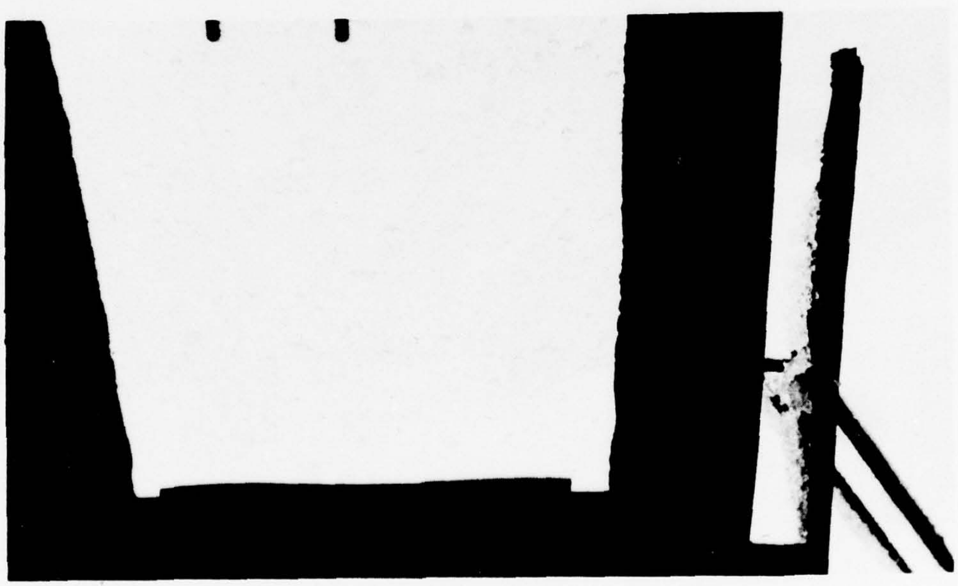

Fig.10.

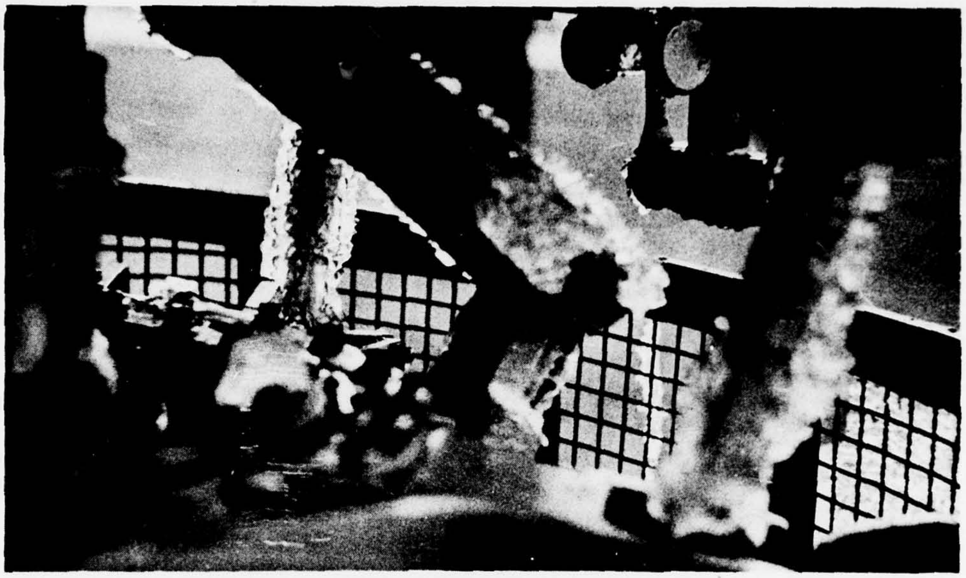

Fig.11.

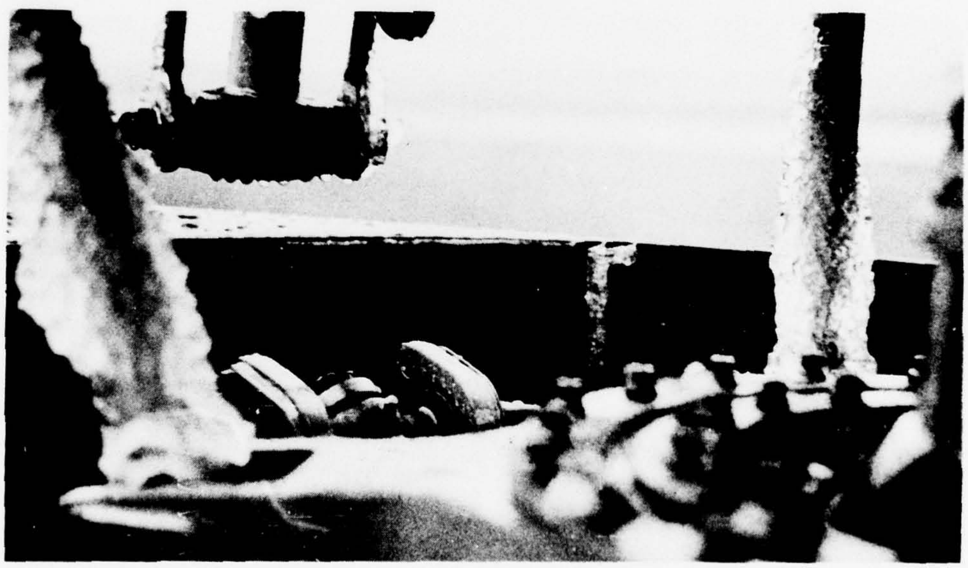

Fig.12.

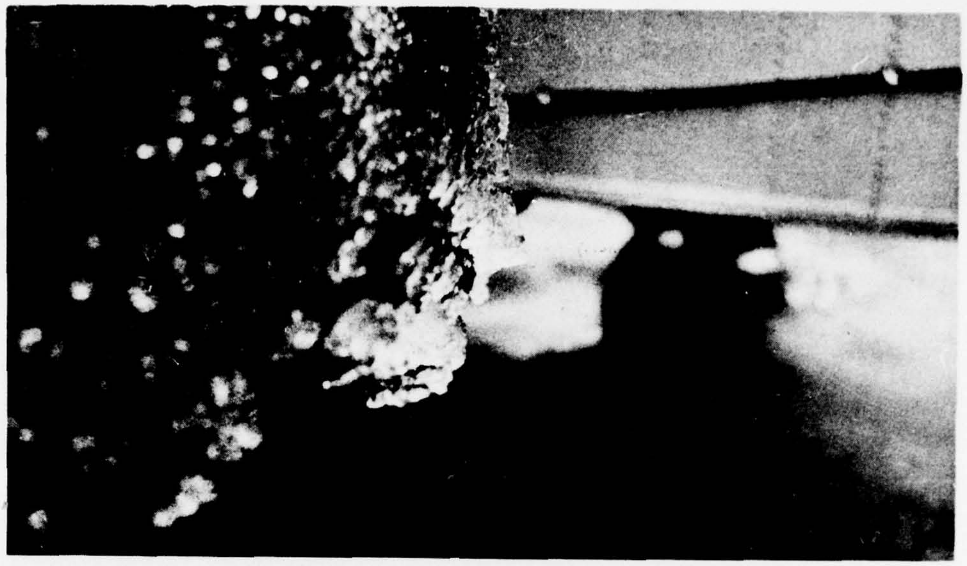

Fig.13.

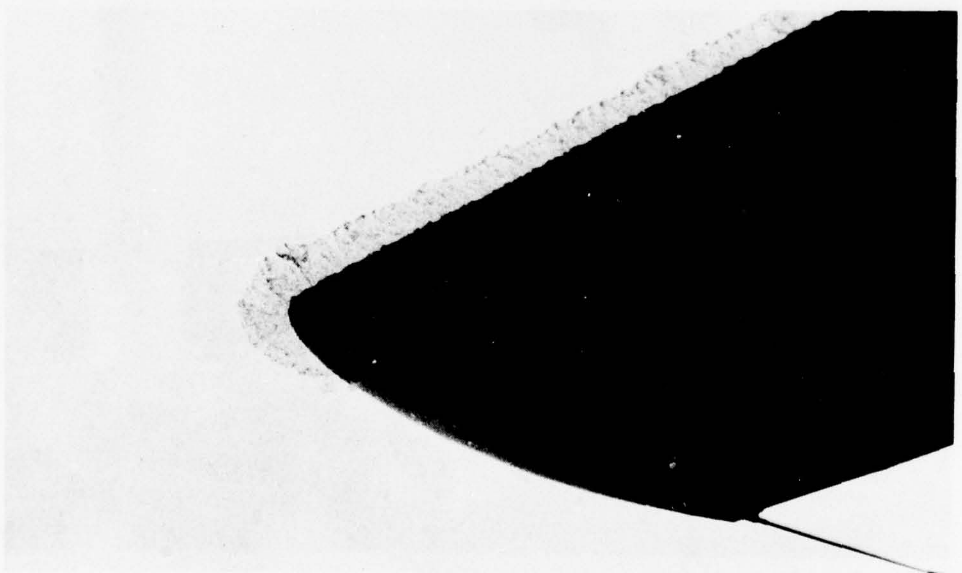

Fig.14.

Fig.15.

HH-53 ICING TESTS

Major Clark Loviern
USAF

6511 Test Support
NAF, El Centro, CA

Major Clark Loviern of the 6511 Test Sp, NAF El Centro, CA narrated a motion picture which highlighted the USAF icing qualification of the HH-53. Major Loviern was project pilot on the qualification. He did not prepare a formal paper for publication, but the spirited discussion which his talk elicited is included.

SESSION III DISCUSSION

Dr. Rosen: I was wondering if you would care to comment, I've had varying comments from various members of the U.K. contigent. I was wondering if you would care to comment on what the Navy's position is on shielding of engine intakes? And on what plans you have for future development of these shields, if any?

CPT Checketts: You're talking of intakes as for example the Sea King.

Dr. Rosen: I've heard various comments of various members of your contigent and since I was pinned down yesterday on a few points I thought I might put you on the spot.

CPT Checketts: We have been testing an ice shield manufactured by, designed originally by a company which name escapes me at the moment, somewhere up in Connecticut. We have this last winter in Canada tried out the Sikorsky ice deflector shields. We have, we think, uncovered some deficiencies with it and perhaps Alan, you might like to say something about this or perhaps Hugh in a moment. We are proposing to go ahead with it and classify it as a modification for fit to our naval Sea Kings. But perhaps Alan could say something about the problems we had with it.

Mr. Wilson: I shall be in fact touching on this in my paper tomorrow, generally on intake design, however, to deal with a specific point, during the trials last winter as CPT Checketts has said, there have been certain deficiencies come to light. Mainly, I think when flying in icing there is evidence of ice building in several vulnerable areas. And certainly evidence that some of this ice when it sheds even at relatively high forward speeds can in fact be ingested by the engine. Similar problems have been also found in snow and as CPT Checketts has said at the moment we are restricting it to forecast icing release for cover over a short period.

Jim Plackis, FAA: You mentioned that you've uncovered no significant tail rotor problems at temperatures to 10^{o} below? Would you conjecture that as the temperature decreases there would probably be an increasing chance of encountering problems?

CPT Checketts: I think Alan again I should say yes, but let Alan Wilson answer that question.

Mr. Wilson: In fact when I mentioned this yesterday I didn't put a -10^{o} limit on it. In fact we have flown down to -19^{o} in

the case of the Sea King for extended periods, always in trace icing without any problems either on the main rotor or the tail rotor. And, I think on the basis if we accept at these lower temperatures corresponding reduction in concentration; no, I don't anticipate there's going to be any real trouble even down to -20^{o}.

CPT Checketts: Our blade development airplane this winter in fact did have a heated tail rotor. But we do not plan to do any further developments specifically in this area, I think I'm right in saying at the moment.

LTC Graham, 2.75 System: You made your statements compared with what was obviously hover flight. Do you really mean that? I sort of feel like your a little bit out of context when you say in one condition you didn't have any trouble and in the other you did and the two conditions weren't the same.

LT T. Eargle: But what I meant when I said similar conditions is similar type icing conditions. In other words we had similar temperatures and liquid water contents that we were flying through. The only difference was the forward flight speed, and I think I made that point that the primary difference on the engines was the fact that we did have the forward flight speed and the ram air effect helping increase the efficiency of the particle separator system.

LTC Graham: Yea, but that's a big difference though.

LT Eargle: Well sure it is, and that's the point. The Marine Corps doesn't use the aircraft primarily in a hover. That's a very short, very small portion of their mission. The great portion of their mission is accomplished in forward flight.

Mr. Lewis: Are you aware of any difference between the rain removal system on the J model and the G Cobras? I noticed that you had very little problem with icing, whereas we did have quite a bit.

LT Eargle: No, I am not. I was really surprised when Jim Reid gave his presentation yesterday and evidently the Army had a big problem with the rain removal system. The only thing I can think of, and I don't have any facts to back this up, but the power package of course is different and I'm just assuming, but I would imagine that the rain removal system on the J model probably has a larger volume and maybe that's the difference. That's the only thing I can really think of, other than I think the systems really do operate pretty much identically.

Mr. Lewis: Can anyone from Bell tell us whether there is a difference?

Mr. Kawa, Bell: We're probably pulling a lot more power to remove the rain using the twin engines as opposed to the single engine configuration. I will check with the expert at the plant to verify this.

Mr. K. Schmidt, Lockheed: You mentioned that there was no appreciable difference in the inlet pressure. Then it is safe

to assume that there was no difference in the pressure of the air coming into the engine, there was no appreciable pressure drop of the air due to ice blockage into the induction system?

LT Eargle: Well, all I can report on is what we got on our results. I mean you saw the screen accumulations. I would normally, if I hadn't done the trials, if someone had showed me a picture like that I would have said we'd have a pretty significant T_5 rise. However, that wasn't the case with us.

You didn't have a pressure gauge to measure the difference in the incoming pressure with or without ice, no?

No, we didn't have a pressure gauge, no, we strictly measured our engine performance by measuring the torque and T_5 rises.

Dr. Rosen: The induction system is actually the classic United Aircraft PT6 inlet induction system which we use also in the S-58T and the reason I believe that you did get performance that looked as good as it did is because you've got such large plenums and even though you did get an accretion rate and growth that was significant, the velocity was still relatively low and that meant that even with the blockage that you saw you were still in a low loss situation. What it really means is that you had a relatively large plenum with a good deal of growth factor put into it for the ice. But you don't get it for nothing gentlemen. You do pay a penalty with this design. We're paying it at Sikorsky as well, with a larger inlet pressure drop. One other thing that does come out, is the device that's used is to scavenge the air flow thru the particle separator (as LT Eargle pointed out) is the engine exhaust, which by the way has to be slightly nozzled to accomplish the proper monentum to create the ejector action in the secondary flow. So all of this does come into it; but I must say the results are really super and in contrast for further operation on the S-58T. I'd like to ask you a question on the ECU unit? You indicated that the screen froze up. Now if I understand the operation of the ECU unit and the air passes thru that screen thru a fan and thru the heat exchanger of the ECU unit. The fan is driven by the turbine which you've mentioned began to whine. I'd say it began to whine because it was loaded up. The system pressure drop thru the fan went up and the fan began to work harder and the turbine had to make up for it. One thing that really interests me is that if that passage is blocked aren't you really lacking a cooling sink on the cool side of the heat exchanger and wouldn't you get direct bleed air out of the engine? Now if so, why didn't your over-temperature

sensor, which I'm sure you have in your system, turn on and turn off the system?

LT Eargle: I don't know.

Mr. Schmidt: In response to that question it has been our experience at Lockheed that the fixed wing aircraft with artic icing provisions on scoops, particularily on the oil cooler and air conditioning system, scoops and air conditioning systems are always designed for the maximum air temperature of 130 or maybe 120°. So, if there is a reduction in air flow it is compensated by the low temperature of the air. So aerodynamic heating is still there with only the anti-icing provisions. Because the air is cool and the reduced air flow does not quite compensate for the reduction temperature and that's the reason.

Dr. Rosen: That's quite correct except for the fact there is no air flow in his system. In other words, there is no flow at all once that screen is blocked. There is no flow at all into the inlet unless he's got a plenum on the other side of the screen and that's what I was trying to ask, is there in fact a plenum on the other side of the screen so that you can draw air directly into the heat exchanger?

LT Eargle: I think there is but I am not sure.

Dr. Rosen: That answers why you did not see any malfunction.

MAJ Brewer, AEFA: I have 2 questions. I'm not that familiar with the spray rig at Ottawa and I wonder how you quantify your icing severity? What determines your icing severity definitions there? What's your cutoff there that says you experienced trace, light, or is there such a thing?

LT Eargle: Well, mainly its a qualitative evaluation between what we see in natural icing compared with what we're seeing in the spray rig. However, based upon the liquid water contents we're using and looking at various weather data that's available on this subject. The rig generally simulates for us according to that data between light and moderate conditions.

MAJ Brewer: There's no time element then, say you'd expose yourself for 30 minutes?

LT Eargle: We compensate for that by increasing the liquid water content to simulate the speed.

MAJ Brewer: The next question is, did you do any autorotative tests with the H1-J and did you see any degradation in rotor rpm?

LT Eargle: No, unfortunately we didn't and we didn't conduct any tests in that direction. We were mainly interested, the main thrust of our test was just to see what the aircraft would do. We did attempt a couple of autorotations; but we found that when we did the ice generally shed off. Since the scope of our tests for this year, at least, was to see exactly what kind of accumulations we were getting we tended to shy away from that. However, we did recommend in our report that's coming out shortly that autorotation performance be investigated in future trials on the aircraft. Really, its a first cut for us this year. We don't by any means consider the tests on this helicopter complete. We'll have to have at least one and probably 2 or 3 more series of tests to work out all the bugs.

MAJ Brewer: The last question, you did say you did fly in freez-int rain?

LT Eargle: Yes we did. Minus 2 to -5^{o} for 60 minutes at a time.

MAJ Brewer: And, there was no run back and refreezing in the plenum?

LT Eargle: Nothing detectable. Really the large droplet size you see in freezing rain generally runs between 2 and 500 microns; and I'm just speculating here, but because the screens didn't accumulate any ice, not even the particle separator screen at the base of the unit accumulated any ice, we're just speculating that the particle separator, because of the ram air effect, etc. was successful in separating the great majority of those droplets before they ever came in contact with the screens.

Unidentified: Did you notice any significant differences in ice accumulation between on the rotor blades between the spray rig and your natural icing?

LT Eargle: They correlated well for similar conditions, for instance, most of our natural icing flights were flown in between trace and light to moderate conditions at temperatures ranging between -9^{o} and -11^{o} and we saw good correlation between similar tests we'd run in the spray rig under those same conditions. As far as the rotor system went, we correlated very well with what we got in the spray rig.

Unidentified: Did you also get asymmetric shedding in the spray rig?

LT Eargle: Yes we did at all temperatures below -5^{o} as well as in natural.

LTC Griffith, AEFA: You said just a second ago that you flew in natural icing with accretion rates of light trace and moderate. How did you determine that those were your icing rates?

LT Eargle: If you remember the picture of the AH-1J, the 20mm cannon located on the front has a natural up slant. Well, in forward flight your attitude is such that that gun barrel was pointed just about perfectly perpendicular to your air flow. I think I'm correct that the standard FAA way to measure ice accretion rate is with a circular tube about 1/2" in diameter. It turned out that our gun barrels very closely simulated those same tubes and we just took the measurements of ice and we knew what air speed we were flying at and we computed a distance for each flight and from that we got a certain amount of ice accretion for a certain distance and we used that to quantify what we were getting in natural icing.

LTC Griffith: So, in other words, what you say was, trace,light or moderate was an average that you saw after a complete flight?

LT Eargle: Oh yes, definitely. We don't have any feel at all for instantaneous rate because we didn't have the instrumentation that the Army did. We don't have any feel at all for what variations that might have existed throughout say a 60 minute run.

LTC Griffith: This could be significant because of what we've seen and I think the English agree that you might fly for 35 minutes and not get anything and then all of a sudden go into severe conditions and ice it up, or some combination thereof and not really know what you've done.

The next question, how did you identify liquid water content in natural conditions? What I'm getting at, is you said that your natural conditions were very closely the same as the spray rig conditions and I'm wondering how you identified your natural conditions as closely as you did?

LT Eargle: We didn't have any direct way of doing that. We only had a comparative basis between what we got in the spray rig and in flight. But that's the best we could do and the only other alternative to that would have been to have something like Calspan up there to calibrate each cloud for us. That costs money though.

Mr. Maurice: Please, what is the limitation for vibration?

LT Eargle: Well, when your eyeballs cage and the instruments can't be read, then thats bad. When you can't read the instruments. Well that's severe.

Dr. Rosen: One point that you made that I wonder if you could comment a bit more on and that's rotor speed excursion and do you feel that this gets you a long way down the road towards controlling the shedding or do you feel that you need some sort of thermal protection system for your blades?

LT Eargle: Quite frankly that will depend on what we come up with in the future. Like I pointed out in the presentation, the thing worked for us every time in both the spray rig and natural icing. However, when your talking about a data base of 6 to 8 flights, thats really not enough to accurately state that yes this works all the time. If we could, I imagine the Marine Corps would consider that a satisfactory compromise to sinking money into a heated system. However, if further tests show in a variety of conditions that the technique is not always very effective then I guess the only other alternative would probably be to go to an electrothermal boot of some type on the blades.

Dr. Rosen: Did you use rotor speed excursion control in both the spray rig and natural icing?

LT Eargle: Yes, if you're asking me if we varied our rotor rpm in order to shed ice in both conditions, yes we did.

Mr. Lewis, AEFA: One point I think we do have to make very clear on the rotor blade excursions, however, is the fact that you were probably able to shed the unbalanced outer ice but you are probably not able to shed the inner ice. At least it's our experience that the inner ice that accumulates on the rotor is very persistent. Then in the case of a twin engine aircraft you may be able to buy this kind of a technique as opposed to the electrothermal deicing. But when your talking about a single engine aircraft you've got to have your autorotative capability or some other solution. So I think really if your looking at that as a panacea to the icing problem, Ken, you're not going to get it.

CPT Checketts: Right, I'd like to thank LT Eargle for a very well presented and very interesting talk.

Jim Hayden, AEFA: We want to thank you for the tremendous dissertation on the fundamental physics concerning ice formation. I think its something that we've been missing up to this point. I want to make a couple of comments and then I'm going to ask John Barbagallo and Bob Tucker to take up the ball.

You mentioned the Air Force C-130. The Air Force also uses a KC-135. I think that their normal air speed ranges are 90 to 150 knots on the C-130 and 150 to 300 with the KC-135. I comment that the little Chinook will do 159 with the boom extended. Another comment, perhaps we could develop cooperative effort (with Mr. Abel of NGTE) in getting Merlin engines because we've got the same problem trying to keep one aircraft in the air.

LT Jaeger, AFFTC: We do have the 2 tankers but 150 knots is kind of slow for our 135. We also have the B-52 calibration aircraft which we have been using on the KC-135 mainly and on it we've found that we have a mean drop of 19 microns which we feel is pretty good. We just got a new spray system in the 135 and the 130 that we haven't been able to calibrate yet, mainly because it hasn't flown since we've had the B-52 modified. Eighty to 150 is a good speed range for it. I can't give you a drop size but it will give you a liquid water content from about 0 to .8 for both airplanes depending on speed, of course. We have 3 different nozzles; 2 icing nozzles, one is a round nozzle which we use right now, it has a 100 nozzles on it. This will give you from 6 to 10 foot round cloud and we also have an oblong nozzle with 50 nozzles which is supposed to give you a more uniform cloud with lower water contents. We also have a rain nozzle which we use for simulated rain tests mainly for the Navy because that's what they are interested in; and that will give you a much larger drop, 100 microns and above. Currently we're interested mainly in the fixed wing icing because we don't have any new helicopters on the way.

SQDN LDR Lake: I'd like to make a comment, if I could, about the so called frozen ice facilities. I think there's going to be from this presentation, we're talking about an extremely delicate mechanism, which requires extremely careful balance to produce a similar effect and I think when we are talking about the larger facilities the condition of the specimen is extremely important; and having observed tests for many years, and done quite a lot of flying, I am personally of the opinion that the mechanism is so delicate that if you disturb it by removing the vehicle from the environment, even for a moment, the results can be extremely misleading. We have great difficulty in saying what we have been through in the natural environment. It is

very easy to say what we think we've been thru in a rig. But it is very difficult if it is a dynamic rig, its behind a tanker or an Ottawa spray rig, to say what proportion of the time we think we spent in the environment we've been controlling. Even more difficult, is, what is the effect of being out of the environment for some time? I would like everybody here when they are planning flight tests to use the rig extremely intelligently and never assume that the effect in natural icing is going to be even anything like the rig effect. I'd just like to ask what the likehood is of running into a cloud that is part ice and part water? Is that condition not thermodynamically unstable?

Mr. Abel: Yes, that is thermodynamically unstable once the ice crystals start to form then the super-cooled water, but you can get snow falling through super-cooled clouds, you get other precipation falling through a super-cooled cloud.

Mr. Wilson: Just an additional point. In the 6 years of testing we've done, the mixed conditions which Mr. Abel referred to are in fact the norm and it's the particle icing which is the exception.

SQDN LDR Lake: We have so far discovered no method of giving the air crew ready warning of flying in light or moderate snow as we have encountered while they are in an icing cloud; and therefore, when we are talking about clearances, we usually have to imply that if we give an icing clearance, we have to be able to handle light or moderate snow as well; and the problem of detection is compounded. We have a bad condition that you could enter without knowing about it; and we haven't yet found a method of warning the air crew that it is happening.

Mr. Wilson: Just one further quick point I'd like to add on to what Hugh Lake said that is the same goes for freezing rain. When your flying in a cloud and you encounter freezing rain, its extremely difficult for the pilot to detect it, because he's too busy flying the aircraft.

Specialist Krynytzky, AEFA: On the Ottawa test tower, have you run into any maximum wind speed in which testing could be carried out; and what is the factor determining the maximum wind speed that you can test in?

Mr. Abel: Well, we've got the experts from Ottawa here; but in the old setup the maximum as far as I remember to be 30 miles per hour; unless there was structural limitation. But the higher the wind speed, the greater amount of gustiness you get.

On some of the films you saw the clouds waving about and you've got to have the cloud sufficiently consistent to be able to keep your helicopter into it. Now I don't know if I've got the figure that this nose used, but I reckon 30 miles a hour is still quite a good maximum, right Rick?

Mr. Ringer, NRC: The structural limitation on the rig now has been raised considerably with the new mast. As far as we're concerned we'll raise the rig, if the pilot is willing to fly at 40 knots within 50 feet of the ground.

Mr. Lewis: One of the terms in your heat transfer equation was conduction and I wonder if you would hypothesize or comment on the differences between metallic or fiberglass or composite plates?

Mr. Abel: Well I tried to keep my lecture from being too theoretical; but as we all know, the rate of conduction through metal is considerably higher than through fiberglass. Fiberglass is not a very good conductor of heat; and its unusual to have a thermal system which is based on fiberglass. Usually, you try and get the good heat conductor as close to the surface as you can. Maybe you've got some other erosion strip or something on the outside; but these are kept as thin as possible. Mainly metal is a good conductor. Sometimes you can't use it; but if you can, do use it. I don't know whether that was quite what you were wanting to get for an answer?

Mr. Lewis: Do you have any test experience with fiberglass blades?

There's been one odd blade I believe; but it wasn't heated thermally. You wouldn't notice, if your talking about the way it happens naturally; I don't think you would notice very much; because you've got heat flowing away through the metal surface. You've also got heat being carried away by the air; and you just get the balance so that the total amount of heat gets taken away. The way in which one can measure these things is still so inaccurate; but you wouldn't know much about it as to which way the heat went, all you'd know is that it went at such and such a time that you can measure. But I agree with you, you'll be able to get it away quicker if you use metal.

Dr. Rosen, Sikorsky: Out of 85 planned flights you indicated 26 encounters with icing conditions. I didn't get the temperature. Did you say it was as low as -13°C?

Mr. Stevens: They had as low as -13, yes.

Dr. Rosen: O.K. Now what sort of torque increase did you see to sustain the flight?

Mr. Stevens: There was about 15 percent increase. They were running about half power, then they went up to 65 percent.

Dr. Rosen: I'd like to ask you a question about the design of the system? Some of this may be proprietary. Is the CH-47 thermal system an add-on boot or is it built into the blade itself?

Mr. Stevens: I'm sorry the CH-47 does not have any. The CH-46 is the one that has the built-in system. That is built into the blade. The 47 has never had anything but the fluid type system. That's the only one that's been on the Chinook.

Dr. Rosen: I'm afraid I got confused there. O.K. What you're saying is that the CH-46 system, the one you described the 7 elements is the CH-46 system?

Mr. Stevens: That's correct.

Dr. Rosen: O.K. and in this current ECP that you have working you are concerned only with engine inlet protection?

Mr. Stevens: That's correct.

Dr. Rosen: I see, thank you.

Mr. Cox: One of your pictures appeared to show ice at the tip. I wasn't able to hear your comment on it; but I wonder if you could explain what the tip velocity was; what aerodynamic heating would be associated with that velocity, and how, taking into consideration the aerodynamic heating, you account for the fact that ice can accrete at a temperature within your range?

Mr. Stevens: Well I can't answer all that here because I don't have the numbers with me; but I'll try it from another direction. The temperature that we were talking about there is -18°C and it's real low temperature; and that, of course, will eliminate the effects of the aerodynamic heating. The proof is the pictures, I mean there was the ice on there. That was taken during

the Air Force tanker test.

What is the tip velocity? That would make a big difference.

Andy, do you, (about roughly 700 feet per second)

You say 700 feet a second. On the A-model, it's 230 rotor rpm on a 60-foot rotor.

CPT Checketts: I think because time is running on I can allow just one more question.

Mr. Schmidt, Lockheed: In conjunction with your tests to assure the structural integrity of the plane I've noticed on your CH-46 helicopter you have a vacuum-type system to assure the integrity of the primary structure, and that there are no cracks in it. Could you describe a little bit that vacuum pull-down system that you have on the CH-46 blades?

Mr. Stevens: No, it's just a bag inside of the spar; and you put a vacuum between the bag and the spar itself and you have an indicator. When the vacuum is lost or is partly lost you get a change in an indicator. It's a visual system that's inspected as a ground inspection item.

Thank you.

CPT Checketts: Thank you Mr. Stevens. We're in danger of a time overrun here; I propose to go on to 11:45.

LT Eargle: I believe you said as a result of your tests you'd been able to obtain commercial certification to fly through light forecast icing conditions, is that correct?

Mr. Atkinson: That's correct.

LT Eargle: Well as the Captain pointed out earlier the reliability of forecasting severity of icing is extremely difficult. How do your pilots quantify what they are flying through?

Mr. Atkinson: Well, we have to rely on forecasts. Let me say first, before we had any form of protection, our operation is a civil one. Most of our work is on the North Sea, in support of Oriex, and they would often go out to an oil rig without any form of protection. Often they would stay on that rig 5 or 6 hours and the weather change and come back through icing conditions. So we have a problem, a big one, one winter we lost 35 days of flying. That's a lot of time for a commercial organization. So we do qualify it by saying that we must always have a let out. Our conditions are the same as yours; so there must be a way out. We normally set a level of 1,000 feet. It's only in forecast icing conditions. They have radar on the aircraft so if they like, they can go around any cloud formations. To be honest, we do not ask any pilot to go into icing conditions unless he wants to. No, I must qualify that, you see; because we have a lot of them and when we did our trials we actually called the pilots doing the main flying. Now the first 2 pilots in the captain's and co-pilot's seat, I must state this to you to try to erase any thought that we were just foolhardy. These 2 pilots are ex-RAF pilots and bomber pilots of WW II. They've flown all around Europe with weather on fixed wing; and they have at least 15 years each on helicopter work. Those 2 men, one was a flight manager, one was the Assistant to the General Manager, did 50 percent of the early flying. They were really qualified pilots and although we did accomplish a lot at no time did we think we were in any danger. I can assure you, I went on every flight and I'm old enough to want to get my pension. But we do qualify icing conditions; and as I said, a lot of our pilots are quite happy to go in and feel the conditions. We get feedback reports which we hope to compile and get more information.

Mr. Schmidt, Lockheed: Does the qualification of icing condition involve a temperature range?

Mr. Atkinson: Oh yes, sorry I didn't say. -5°.

Mr. Schmidt: You don't fly in icing at temperatures lower than -5°?

Mr. Atkinson: No.

Mr. Schmidt: Thank you.

Mr. Atkinson: This was rather a rushed paper and a lot of work that has been done is not included.

Mr. Lewis: Was there any evidence in an increase in vibration that might have been due to icing of the bi-filar vibration absorber and thereby reducing its effectiveness?

Mr. Atkinson: Yes, I have brought 20 copies of our detailed report on these trials if anyone is interested they will find graphs showing all parameters on them. We did experience asymmetrical shedding on the rotor blades in temperatures around about -8.5°. We had a vertical vibration increase from .2g to .4g in the worst case. We had a lateral vibration increase yes, we did get an increase in vibration. We always found, or at least the pilot's found that if they reduced speed, and obviously reduced altitude, they soon came out of the condition. We never experienced any condition which, alright they were a little bit frightening when they were first encountered, but when we first encountered this heavy vibration, we came out and went back in again within 5 minutes to get a recording and did a 3 or 4 minute run, so yes we had increased vibration. We didn't consider it was excessive.

Thank you.

CPT Checketts: Gentlemen, that concludes the morning session.

MAJ Loviern: Induced shedding was of no value at all. We tried quite violent cyclic maneuvers and changes of power from an autorotation although we didn't test autorotation as far as skin ice up and then autorotate. We would go into autorotation and then change to max available power and nothing seemed to help enough to warrant going through all those maneuvers. That was our end result and it did take care of itself quite nicely.

(Question was too far from microphone to hear)

John said the one thing we did try also was the rpm change. He actually specifically mentioned reduce rpm and that seemed to do the most good. But we would change it through the full operating range in flight range of rpm and the reduced rpm did the most good of anything to induce shedding.

Mr. Tolliver, EGLIN: Just a segment about the silicone for ice shedding. We did several settings of different types of silicone compounds and we found that silicone will indeed shed glaze ice, or clear ice, but has little or no effect on rim ice. So I don't know what their icing conditions were but we have not been able to do anything with silicone toward rime ice.

O.K. Thank you. Like I say that just seemed interesting and it worked for them under their conditions and they certainly aren't going to do, a whole lot of modifications with their little fleet of aircraft, but I thought it was kind of interesting and maybe warranted some further investigation by somebody. I didn't know what you had done.

Mr. Bender, AEFA: You've mentioned that you had periodic accretions and then shedding of ice. I was wondering what period that was?

Oh, I'd have to let John field that really if he has it in his head fine, otherwise I'll have to go to the report for that. Again this is similar to the CH-47. We'd run about 2 to 4 minutes in cycle.

LTC Graham from 2.75 System: I just wanted to use this opportunity to make a comment. Your qualification of the aircraft without testing its autorotative capability. During just the last day and three fourths of this symposium its pretty evident that even the 3 U.S. services do not have the same criteria for practically the same airplanes and the Navy test of the Cobra without ever

measuring the vibration levels. You all certified a helicopter without measuring autorotations and you know, the thing that came about is that, everybody can't be right, otherwise we would have a standard procedure and a standard set of criteria as to what the envelope must be certified.

MAJ Loviern: That's right. I can appreciate what you say but maybe we are all right but only as far as we go. Plus the fact this being a multi-engine aircraft is one thing; and you know since testing a single engine aircraft maybe autorotation is a little bit more important thing to check.

John Barbagallo, AFFTC: I'd like to mention here that the largest torque increase that we experience was less than 15 percent.

Oh my, I, during our tests I don't remember what our maximum weight was? We did vary it quite a bit. Our trip back our natural icing encounter we were close to max gross. We took off out of El Paso and our max allowable at the time was 42,000 lbs. We got really good icing there. I forgot the target now but we just watched it build up. We got like an 1/8" and then 1/4" within just a very few minutes and being at that high gross weight and because of the cruise guide, we had to slow down. As you know the 53 is limited by the cruise guide meter at higher altitude and gross weights.

Frank Duke, Boeing Vertol: Do you have any comment regarding the ice accumulation on the horizontal stabilizer? Was it evident in either the stick position, longitudinal flying qualities, or the AFCS behavior?

MAJ Loviern: No, not one indication of it at all.

Mr. Duke: Did you accumulate a lot on it?

MAJ Loviern: Yes, not any more than you saw on the vertical fin in the movie. It was quite a bit on, I never could tell on the controls or the AFCS functioning of any change at all because of icing.

SQDN LDR Lake: Did you have, apart from expressions like "we had 1/4" in a couple of minutes," any indication or any record of icing rates and on how long these high rates lasted? And did you do any flight envelope investigations to see how close to the corners of the envelope you were at when you had these higher torque increments and whether the response of the cruise guide was different when you found high cruise guide readings at lower

speeds than you'd normally find on the clean aircraft?

No we specifically didn't look at changes in cruise guide settings like John said the highest increase in torque we got for the same speed and gross weight was about 15% and that's only when we had the very most severe icing and then it would shed when we'd go back to a lower power setting. Yes, we did look at some of the performance but that wasn't our job at this time but because the thing could fly with some ice on it, we were then prompted to say "well then what does it do to the performance?" and we did take a little bit of that data, nothing that sticks in my head right now as having been terrible significant or limiting the thing at all; truthfully I'd have to go back to our report and our data.

MAJ Brewer: I'm curious in your subsequent testing in Elmendorf if you had any problems with snow ingestion in the engines? I'm anxious to hear what our English friends are going to say later about that.

MAJ Loviern: No, we sure didn't. We didn't have much of an opportunity for that either. We flew through some quite heavy snow on just a couple of occasions. From our operating area we were able to do some hovering in our departure staging area with some snow; but we never saw that there was a problem of any kind.

MAJ Brewer: And another question on the rotor brake application after your flights. Did you find it you had a rapid application, did you have shedding of the blades or did you just use a normal braking procedure and not have any problem with ice being shed during the shutdown?

MAJ Loviern: No, we did have problems with ice being shed during shutdown. I think that's where our problems in the tail rotor blades came from, but we tried several things and when we would break very fast we'd have a little bit more shedding then otherwise. Rather than just let them coast down entirely by themselves, we would use some braking; but we got to use less and less so we could keep as much ice on the blades as possible for pictures and investigation.

Dr. Rosen, Sikorsky: I just want to make a couple of points. When we set 80 knots in the original design as the speed in which we would open the by-pass doors on the engine particle separator, we did this not to limit the operation in icing conditions but to capture some ram at speeds greater than that point. So there was never any intent on our part to limit the helicopter that way. I must say we were delighted with the performance of the particle

separator. I don't regret being an old lady at the time, because I think we had quite a lot to risk. I'd like to also point out that some of you may want to see some of John's pictures. The ice formation on the tubes in the particle separator very interestingly confirms the accretion rates that I showed you yesterday on the CH-54 particle separator, which we tested in the Cleveland Icing Research Tunnel, at a speed of about 126 miles per hour. So there's a case where component testing does seem to confirm in a similar phenomenon what you are seeing in actual flight conditions.

MAJ Loviern: I didn't mean to imply anything about the particle separators in icing or you limiting the aircraft. I know they weren't built with icing in mind truthfully; and once you get to 80 knots, you ought to be out of hover and all that dust; and they should be coming open. But once we found that they operated so nicely in ice, then, we thought, well let's expand that envelope; and see if we can't keep those doors closed and, in fact, it worked quite nicely.

Horn, USNTPS: You claim you have a clearance for moderate icing conditions. Could you be more precise in terms of heights and temperatures to what that clearance is?

MAJ Loviern: That's a very defined thing, moderate icing for - John, do you have a description of moderate ice?

John Barbagallo: I think LT Jaeger here could answer this better. The Air Force issues the standard definition in the flight manual. We weren't restricted by spelling out temperatures of this sort of thing. Fred, did you want to identify?

LT Jaeger: It's an accretion rate is what it is. We use the standard FAA definitions and there was no other identifier added to that.

MAJ Loviern: Thank you very much. I certainly appreciate the opportunity to come and talk with you and try to answer some of your questions.

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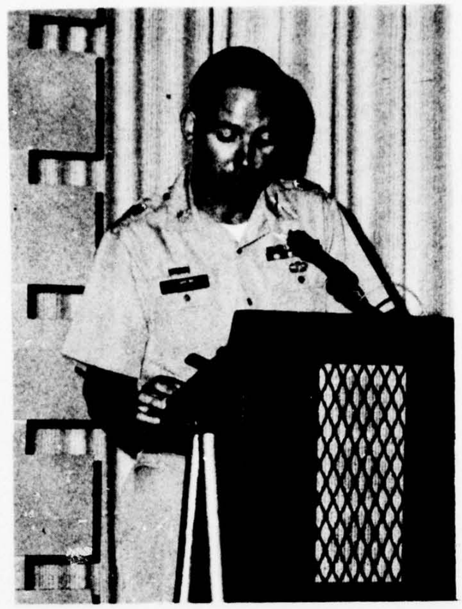

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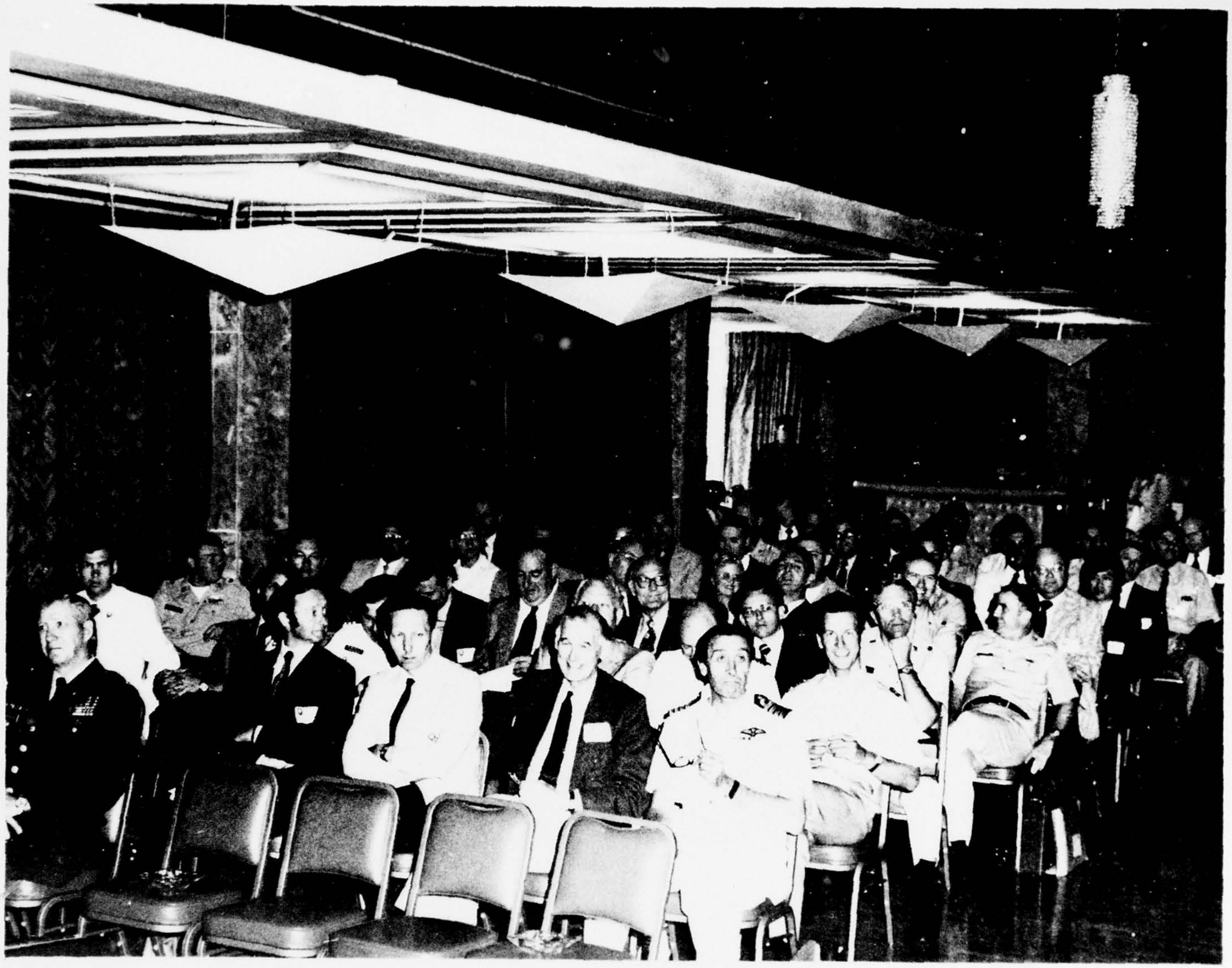

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